

US009247117B2

(12) **United States Patent**  
**Duparré**

(10) **Patent No.:** **US 9,247,117 B2**  
(45) **Date of Patent:** **Jan. 26, 2016**

(54) **SYSTEMS AND METHODS FOR CORRECTING FOR WARPAGE OF A SENSOR ARRAY IN AN ARRAY CAMERA MODULE BY INTRODUCING WARPAGE INTO A FOCAL PLANE OF A LENS STACK ARRAY**

(58) **Field of Classification Search**  
CPC ..... H04N 5/23232; H04N 5/3415; H04N 3/1593; H04N 3/335; G03B 37/04  
See application file for complete search history.

(71) Applicant: **Pelican Imaging Corporation**, Santa Clara, CA (US)

(56) **References Cited**

U.S. PATENT DOCUMENTS

(72) Inventor: **Jacques Duparré**, Jena (DE)

4,124,798 A	11/1978	Thompson
4,198,646 A	4/1980	Alexander et al.
4,323,925 A	4/1982	Abell et al.
4,460,449 A	7/1984	Montalbano
4,467,365 A	8/1984	Murayama et al.

(73) Assignee: **Pelican Imaging Corporation**, Santa Clara, CA (US)

(Continued)

(\*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

FOREIGN PATENT DOCUMENTS

(21) Appl. No.: **14/484,154**

EP	840502 A2	5/1998
EP	2336816 A2	6/2011

(Continued)

(22) Filed: **Sep. 11, 2014**

OTHER PUBLICATIONS

(65) **Prior Publication Data**

US 2015/0288861 A1 Oct. 8, 2015

Muehlebach, "Camera Auto Exposure Control for VSLAM Applications", Studies on Mechatronics, Swiss Federal Institute of Technology Zurich, Autumn Term 2010 course, 67 pgs.

(Continued)

**Related U.S. Application Data**

(60) Provisional application No. 61/976,335, filed on Apr. 7, 2014.

*Primary Examiner* — Tuan Ho

(74) *Attorney, Agent, or Firm* — KPPB LLP

(51) **Int. Cl.**

<b>H04N 5/335</b>	(2011.01)
<b>H04N 5/225</b>	(2006.01)
<b>G02B 3/00</b>	(2006.01)
<b>G02B 27/00</b>	(2006.01)
<b>H04N 5/247</b>	(2006.01)

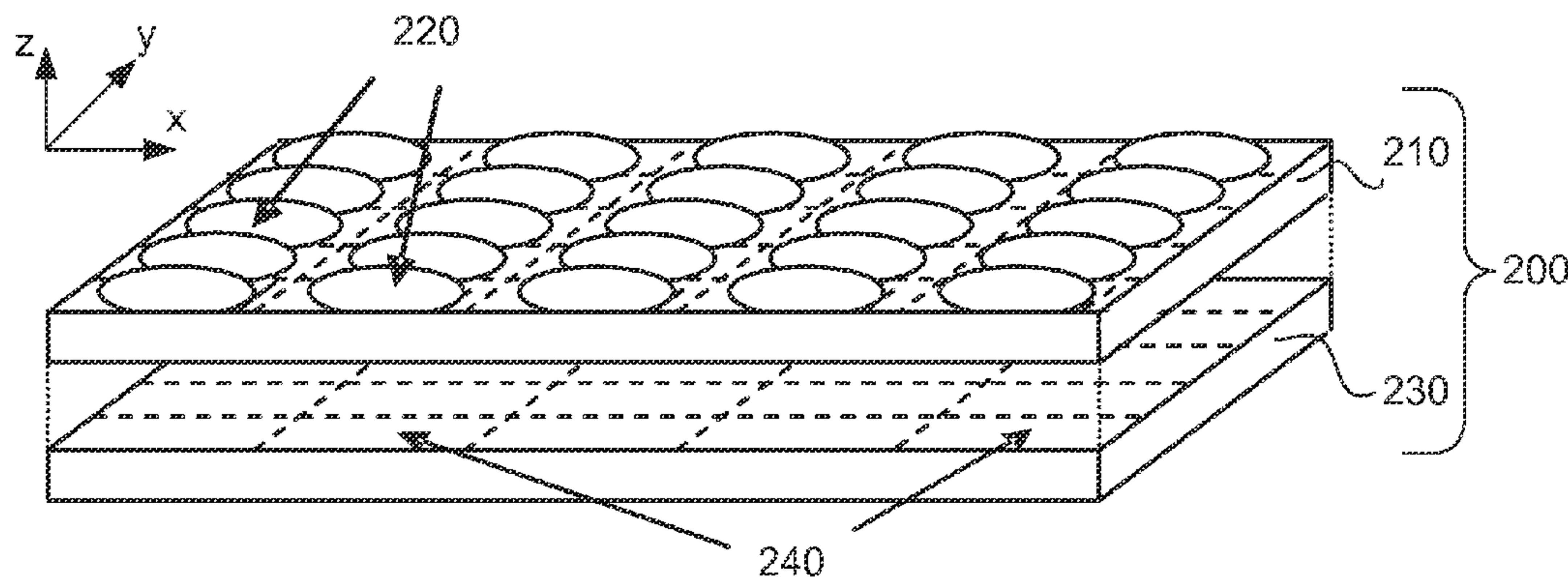
(57) **ABSTRACT**

Systems and methods in accordance with embodiments of the invention provide an array camera module in which warpage is designed into the projection plane of images from a lens stack array to correct for warpage in a sensor of the array camera module. The resulting array camera modules has back focal lengths for each of the lens stacks in the lens stack array that are substantially consistent when placed over a sensor.

(52) **U.S. Cl.**

CPC ..... **H04N 5/2254** (2013.01); **G02B 3/0012** (2013.01); **G02B 3/0062** (2013.01); **G02B 27/0025** (2013.01); **H04N 5/2258** (2013.01); **H04N 5/247** (2013.01)

**18 Claims, 10 Drawing Sheets**



(56)

## References Cited

## U.S. PATENT DOCUMENTS

5,005,083	A	4/1991	Grage	8,131,097	B2	3/2012	Lelescu et al.
5,070,414	A	12/1991	Tsutsumi	8,164,629	B1	4/2012	Zhang
5,144,448	A	9/1992	Hornbaker	8,180,145	B2	5/2012	Wu et al.
5,327,125	A	7/1994	Iwase et al.	8,189,089	B1	5/2012	Georgiev
5,629,524	A	5/1997	Stettner et al.	8,213,711	B2	7/2012	Tam
5,808,350	A	9/1998	Jack et al.	8,231,814	B2	7/2012	Duparre
5,832,312	A	11/1998	Rieger et al.	8,242,426	B2	8/2012	Ward et al.
5,880,691	A	3/1999	Fossum et al.	8,244,027	B2	8/2012	Takahashi
5,933,190	A	8/1999	Dierickx et al.	8,254,668	B2	8/2012	Mashitani et al.
5,973,844	A	10/1999	Burger	8,279,325	B2	10/2012	Pitts et al.
6,002,743	A	12/1999	Telymonde	8,280,194	B2	10/2012	Wong et al.
6,034,690	A	3/2000	Gallery et al.	8,294,099	B2	10/2012	Blackwell, Jr.
6,069,351	A	5/2000	Mack	8,305,456	B1	11/2012	McMahon
6,069,365	A	5/2000	Chow et al.	8,315,476	B1	11/2012	Georgiev et al.
6,097,394	A	8/2000	Levoy et al.	8,345,144	B1	1/2013	Georgiev et al.
6,124,974	A	9/2000	Burger	8,360,574	B2	1/2013	Ishak et al.
6,130,786	A	10/2000	Osawa et al.	8,400,555	B1	3/2013	Georgiev
6,137,535	A	10/2000	Meyers	8,406,562	B2	3/2013	Bassi et al.
6,141,048	A	10/2000	Meyers	8,446,492	B2	5/2013	Nakano et al.
6,160,909	A	12/2000	Melen	8,514,491	B2	8/2013	Duparre
6,163,414	A	12/2000	Kikuchi et al.	8,541,730	B2	9/2013	Inuiya
6,205,241	B1	3/2001	Melen	8,542,933	B2	9/2013	Venkataraman et al.
6,340,994	B1	1/2002	Margulis et al.	8,553,093	B2	10/2013	Wong et al.
6,358,862	B1	3/2002	Ireland et al.	8,559,756	B2	10/2013	Georgiev et al.
6,477,260	B1	11/2002	Shimomura	8,619,082	B1	12/2013	Ciurea et al.
6,563,537	B1	5/2003	Kawamura et al.	8,655,052	B2	2/2014	Spooner et al.
6,603,513	B1	8/2003	Berezin	8,682,107	B2	3/2014	Yoon et al.
6,611,289	B1	8/2003	Yu	8,692,893	B2	4/2014	McMahon
6,627,896	B1	9/2003	Hashimoto et al.	8,773,536	B1	7/2014	Zhang
6,628,330	B1	9/2003	Lin	8,780,113	B1	7/2014	Ciurea et al.
6,635,941	B2	10/2003	Suda	8,804,255	B2	8/2014	Duparre
6,657,218	B2	12/2003	Noda	8,830,375	B2	9/2014	Ludwig
6,671,399	B1	12/2003	Berestov	8,831,367	B2	9/2014	Venkataraman et al.
6,750,904	B1	6/2004	Lambert	8,854,462	B2	10/2014	Herbin et al.
6,765,617	B1	7/2004	Tangen et al.	8,861,089	B2	10/2014	Duparre
6,771,833	B1	8/2004	Edgar	8,866,912	B2	10/2014	Mullis
6,774,941	B1	8/2004	Boisvert et al.	8,866,920	B2	10/2014	Venkataraman et al.
6,795,253	B2	9/2004	Shinohara	8,878,950	B2	11/2014	Lelescu et al.
6,819,358	B1	11/2004	Kagle et al.	8,885,059	B1	11/2014	Venkataraman et al.
6,879,735	B1	4/2005	Portniaguine et al.	8,896,594	B2	11/2014	Xiong et al.
6,903,770	B1	6/2005	Kobayashi et al.	8,896,719	B1	11/2014	Venkataraman et al.
6,909,121	B2	6/2005	Nishikawa	8,902,321	B2	12/2014	Venkataraman et al.
6,958,862	B1	10/2005	Joseph	2001/0005225	A1	6/2001	Clark et al.
7,085,409	B2	8/2006	Sawhney et al.	2001/0019621	A1	9/2001	Hanna et al.
7,161,614	B1	1/2007	Yamashita et al.	2001/0038387	A1	11/2001	Tomooka et al.
7,199,348	B2	4/2007	Olsen et al.	2002/0012056	A1	1/2002	Trevino
7,262,799	B2	8/2007	Suda	2002/0027608	A1	3/2002	Johnson
7,292,735	B2	11/2007	Blake et al.	2002/0039438	A1	4/2002	Mori et al.
7,295,697	B1	11/2007	Satoh	2002/0063807	A1	5/2002	Margulis
7,369,165	B2	5/2008	Bosco et al.	2002/0087403	A1	7/2002	Meyers et al.
7,391,572	B2	6/2008	Jacobowitz et al.	2002/0089596	A1	7/2002	Suda
7,408,725	B2	8/2008	Sato	2002/0094027	A1	7/2002	Sato et al.
7,606,484	B1	10/2009	Richards et al.	2002/0101528	A1	8/2002	Lee
7,633,511	B2	12/2009	Shum et al.	2002/0113867	A1	8/2002	Takigawa et al.
7,646,549	B2	1/2010	Zalevsky et al.	2002/0113888	A1	8/2002	Sonoda et al.
7,657,090	B2	2/2010	Omatsu et al.	2002/0163054	A1	11/2002	Suda et al.
7,675,080	B2	3/2010	Boettiger	2002/0167537	A1	11/2002	Trajkovic
7,675,681	B2	3/2010	Tomikawa et al.	2002/0177054	A1	11/2002	Saitoh et al.
7,706,634	B2	4/2010	Schmitt et al.	2003/0025227	A1	2/2003	Daniell
7,723,662	B2	5/2010	Levoy et al.	2003/0086079	A1	5/2003	Barth et al.
7,782,364	B2	8/2010	Smith	2003/0124763	A1	7/2003	Fan et al.
7,826,153	B2	11/2010	Hong	2003/0140347	A1	7/2003	Varsa
7,840,067	B2	11/2010	Shen et al.	2003/0179418	A1	9/2003	Wengender et al.
7,912,673	B2	3/2011	Hébert et al.	2003/0190072	A1	10/2003	Adkins et al.
7,986,018	B2	7/2011	Rennie	2003/0211405	A1	11/2003	Venkataraman
7,990,447	B2	8/2011	Honda et al.	2004/0008271	A1	1/2004	Hagimori et al.
8,000,498	B2	8/2011	Shih et al.	2004/0012689	A1	1/2004	Tinnerino
8,013,904	B2	9/2011	Tan et al.	2004/0027358	A1	2/2004	Nakao
8,027,531	B2	9/2011	Wilburn et al.	2004/0047274	A1	3/2004	Amanai
8,044,994	B2	10/2011	Vetro et al.	2004/0050104	A1	3/2004	Ghosh et al.
8,077,245	B2	12/2011	Adamo et al.	2004/0056966	A1	3/2004	Schechner et al.
8,098,304	B2	1/2012	Pinto et al.	2004/0066454	A1	4/2004	Otani et al.
8,106,949	B2	1/2012	Tan et al.	2004/0100570	A1	5/2004	Shizukuishi
8,126,279	B2	2/2012	Marcellin et al.	2004/0114807	A1	6/2004	Lelescu et al.
8,130,120	B2	3/2012	Kawabata et al.	2004/0151401	A1	8/2004	Sawhney et al.
				2004/0165090	A1	8/2004	Ning
				2004/0169617	A1	9/2004	Yelton et al.
				2004/0170340	A1	9/2004	Tipping et al.
				2004/0174439	A1	9/2004	Upton



(56)

References Cited

U.S. PATENT DOCUMENTS

2004/0179834	A1	9/2004	Szajewski	2007/0257184	A1	11/2007	Olsen et al.
2004/0207836	A1	10/2004	Chhibber et al.	2007/0258006	A1	11/2007	Olsen et al.
2004/0213449	A1	10/2004	Safae-Rad et al.	2007/0258706	A1	11/2007	Raskar et al.
2004/0218809	A1	11/2004	Blake et al.	2007/0263114	A1	11/2007	Gurevich et al.
2004/0234873	A1	11/2004	Venkataraman	2007/0268374	A1	11/2007	Robinson
2004/0240052	A1	12/2004	Minefuji et al.	2007/0296835	A1	12/2007	Olsen et al.
2004/0251509	A1	12/2004	Choi	2008/0019611	A1	1/2008	Larkin
2004/0264806	A1	12/2004	Herley	2008/0024683	A1	1/2008	Damera-Venkata et al.
2005/0006477	A1	1/2005	Patel	2008/0025649	A1	1/2008	Liu et al.
2005/0012035	A1	1/2005	Miller	2008/0030597	A1	2/2008	Olsen et al.
2005/0036778	A1	2/2005	DeMonte	2008/0043095	A1	2/2008	Vetro et al.
2005/0047678	A1	3/2005	Jones et al.	2008/0043096	A1	2/2008	Vetro et al.
2005/0048690	A1	3/2005	Yamamoto	2008/0062164	A1	3/2008	Bassi et al.
2005/0068436	A1	3/2005	Fraenkel et al.	2008/0079805	A1	4/2008	Takagi et al.
2005/0132098	A1	6/2005	Sonoda et al.	2008/0080028	A1	4/2008	Bakin et al.
2005/0134712	A1	6/2005	Gruhlke et al.	2008/0084486	A1	4/2008	Enge et al.
2005/0147277	A1	7/2005	Higaki et al.	2008/0088793	A1	4/2008	Sverdrup et al.
2005/0151759	A1	7/2005	Gonzalez-Banos et al.	2008/0095523	A1	4/2008	Schilling-Benz et al.
2005/0175257	A1	8/2005	Kuroki	2008/0112635	A1	5/2008	Kondo et al.
2005/0185711	A1	8/2005	Pfister et al.	2008/0118241	A1	5/2008	Tekolste et al.
2005/0205785	A1	9/2005	Hornback et al.	2008/0131019	A1	6/2008	Ng
2005/0219363	A1	10/2005	Kohler	2008/0131107	A1	6/2008	Ueno
2005/0225654	A1	10/2005	Feldman et al.	2008/0151097	A1	6/2008	Chen et al.
2005/0275946	A1	12/2005	Choo et al.	2008/0152215	A1	6/2008	Horie et al.
2005/0286612	A1	12/2005	Takanashi	2008/0152296	A1	6/2008	Oh et al.
2006/0002635	A1	1/2006	Nestares et al.	2008/0158259	A1	7/2008	Kempf et al.
2006/0023197	A1	2/2006	Joel	2008/0158375	A1	7/2008	Kakkori et al.
2006/0023314	A1	2/2006	Boettiger et al.	2008/0187305	A1	8/2008	Raskar et al.
2006/0033005	A1	2/2006	Jerdev et al.	2008/0193026	A1	8/2008	Horie et al.
2006/0038891	A1	2/2006	Okutomi et al.	2008/0218610	A1	9/2008	Chapman et al.
2006/0049930	A1	3/2006	Zruya et al.	2008/0219654	A1	9/2008	Border et al.
2006/0054780	A1	3/2006	Garrood et al.	2008/0240598	A1	10/2008	Hasegawa
2006/0054782	A1	3/2006	Olsen et al.	2008/0246866	A1*	10/2008	Kinoshita ..... G02B 7/02 348/294
2006/0055811	A1	3/2006	Frtiz et al.	2008/0247638	A1	10/2008	Tanida et al.
2006/0069478	A1	3/2006	Iwama	2008/0247653	A1	10/2008	Moussavi et al.
2006/0072029	A1	4/2006	Miyatake et al.	2008/0272416	A1	11/2008	Yun
2006/0087747	A1	4/2006	Ohzawa et al.	2008/0273751	A1	11/2008	Yuan et al.
2006/0098888	A1	5/2006	Morishita	2008/0278591	A1	11/2008	Barna et al.
2006/0125936	A1	6/2006	Gruhike et al.	2008/0298674	A1	12/2008	Baker et al.
2006/0138322	A1	6/2006	Costello et al.	2009/0050946	A1	2/2009	Duparre et al.
2006/0152803	A1	7/2006	Provitola	2009/0052743	A1	2/2009	Techmer
2006/0157640	A1	7/2006	Perlman et al.	2009/0060281	A1	3/2009	Tanida et al.
2006/0159369	A1	7/2006	Young	2009/0086074	A1	4/2009	Li et al.
2006/0176566	A1	8/2006	Boettiger et al.	2009/0091806	A1	4/2009	Inuiya
2006/0187338	A1	8/2006	May et al.	2009/0096050	A1	4/2009	Park
2006/0203113	A1	9/2006	Wada et al.	2009/0102956	A1	4/2009	Georgiev
2006/0210186	A1	9/2006	Berkner	2009/0109306	A1	4/2009	Shan et al.
2006/0239549	A1	10/2006	Kelly et al.	2009/0128833	A1	5/2009	Yahav
2006/0243889	A1	11/2006	Farnworth et al.	2009/0167922	A1	7/2009	Perlman et al.
2006/0251410	A1	11/2006	Trutna	2009/0179142	A1	7/2009	Duparre et al.
2006/0274174	A1	12/2006	Tewinkle	2009/0180021	A1	7/2009	Kikuchi et al.
2006/0278948	A1	12/2006	Yamaguchi et al.	2009/0200622	A1	8/2009	Tai et al.
2006/0279648	A1	12/2006	Senba et al.	2009/0201371	A1	8/2009	Matsuda et al.
2007/0002159	A1	1/2007	Olsen et al.	2009/0207235	A1	8/2009	Francini et al.
2007/0024614	A1	2/2007	Tam	2009/0225203	A1	9/2009	Tanida et al.
2007/0036427	A1	2/2007	Nakamura et al.	2009/0237520	A1	9/2009	Kaneko et al.
2007/0040828	A1	2/2007	Zalevsky et al.	2009/0263017	A1	10/2009	Tanbakuchi
2007/0040922	A1	2/2007	McKee et al.	2009/0268192	A1	10/2009	Koenck et al.
2007/0041391	A1	2/2007	Lin et al.	2009/0268970	A1	10/2009	Babacan et al.
2007/0052825	A1	3/2007	Cho	2009/0268983	A1	10/2009	Stone et al.
2007/0083114	A1	4/2007	Yang et al.	2009/0274387	A1	11/2009	Jin
2007/0085917	A1	4/2007	Kobayashi	2009/0284651	A1	11/2009	Srinivasan
2007/0102622	A1	5/2007	Olsen et al.	2009/0297056	A1	12/2009	Lelescu et al.
2007/0126898	A1	6/2007	Feldman	2009/0302205	A9	12/2009	Olsen et al.
2007/0127831	A1	6/2007	Venkataraman	2009/0323195	A1	12/2009	Hembree et al.
2007/0139333	A1	6/2007	Sato et al.	2009/0323206	A1	12/2009	Oliver et al.
2007/0146511	A1	6/2007	Kinoshita et al.	2009/0324118	A1	12/2009	Maslov et al.
2007/0158427	A1	7/2007	Zhu et al.	2010/0002126	A1	1/2010	Wenstrand et al.
2007/0159541	A1	7/2007	Sparks et al.	2010/0002313	A1	1/2010	Duparre et al.
2007/0160310	A1	7/2007	Tanida et al.	2010/0002314	A1	1/2010	Duparre
2007/0165931	A1	7/2007	Higaki	2010/0013927	A1	1/2010	Nixon
2007/0171290	A1	7/2007	Kroger	2010/0053342	A1	3/2010	Hwang et al.
2007/0211164	A1	9/2007	Olsen et al.	2010/0053600	A1	3/2010	Tanida et al.
2007/0216765	A1	9/2007	Wong et al.	2010/0060746	A9	3/2010	Olsen et al.
2007/0228256	A1	10/2007	Mentzer	2010/0085425	A1	4/2010	Tan
				2010/0086227	A1	4/2010	Sun et al.
				2010/0091389	A1	4/2010	Henriksen et al.
				2010/0097491	A1	4/2010	Farina et al.



(56)

References Cited

U.S. PATENT DOCUMENTS

2010/0103259	A1	4/2010	Tanida et al.	2012/0229628	A1	9/2012	Ishiyama et al.
2010/0103308	A1	4/2010	Butterfield et al.	2012/0249550	A1	10/2012	Akeley et al.
2010/0111444	A1	5/2010	Coffman	2012/0262607	A1	10/2012	Shimura et al.
2010/0118127	A1	5/2010	Nam et al.	2012/0287291	A1	11/2012	McMahon et al.
2010/0133230	A1	6/2010	Henriksen et al.	2012/0293695	A1	11/2012	Tanaka
2010/0141802	A1	6/2010	Knight et al.	2012/0314033	A1	12/2012	Lee et al.
2010/0142839	A1	6/2010	Lakus-Becker	2012/0327222	A1	12/2012	Ng et al.
2010/0157073	A1	6/2010	Kondo et al.	2013/0002828	A1	1/2013	Ding et al.
2010/0165152	A1	7/2010	Lim	2013/0003184	A1	1/2013	Duparre
2010/0177411	A1	7/2010	Hegde et al.	2013/0010073	A1	1/2013	Do
2010/0194901	A1	8/2010	van Hoorebeke et al.	2013/0022111	A1	1/2013	Chen et al.
2010/0195716	A1	8/2010	Klein et al.	2013/0027580	A1	1/2013	Olsen et al.
2010/0201834	A1	8/2010	Maruyama et al.	2013/0033579	A1	2/2013	Wajs
2010/0208100	A9	8/2010	Olsen et al.	2013/0050504	A1	2/2013	Safaei-Rad et al.
2010/0220212	A1	9/2010	Perlman et al.	2013/0050526	A1	2/2013	Keelan
2010/0231285	A1	9/2010	Boomer et al.	2013/0057710	A1	3/2013	McMahon
2010/0244165	A1	9/2010	Lake et al.	2013/0070060	A1	3/2013	Chatterjee
2010/0265385	A1	10/2010	Knight et al.	2013/0076967	A1	3/2013	Brunner et al.
2010/0281070	A1	11/2010	Chan et al.	2013/0077880	A1	3/2013	Venkataraman et al.
2010/0302423	A1	12/2010	Adams, Jr. et al.	2013/0077882	A1	3/2013	Venkataraman et al.
2010/0321640	A1	12/2010	Yeh et al.	2013/0088637	A1	4/2013	Duparre
2011/0001037	A1	1/2011	Tewinkle	2013/0113899	A1	5/2013	Morohoshi et al.
2011/0018973	A1	1/2011	Takayama	2013/0120605	A1	5/2013	Georgiev et al.
2011/0032370	A1	2/2011	Ludwig	2013/0128068	A1	5/2013	Georgiev et al.
2011/0043661	A1	2/2011	Podoleanu	2013/0128069	A1	5/2013	Georgiev et al.
2011/0043665	A1	2/2011	Ogasahara	2013/0128087	A1	5/2013	Georgiev et al.
2011/0043668	A1	2/2011	McKinnon et al.	2013/0128121	A1	5/2013	Agarwala et al.
2011/0069189	A1	3/2011	Venkataraman et al.	2013/0147979	A1	6/2013	McMahon et al.
2011/0080487	A1	4/2011	Venkataraman et al.	2013/0215108	A1	8/2013	McMahon et al.
2011/0108708	A1	5/2011	Olsen et al.	2013/0222556	A1	8/2013	Shimada
2011/0121421	A1	5/2011	Charbon et al.	2013/0229540	A1	9/2013	Farina et al.
2011/0122308	A1	5/2011	Duparre	2013/0259317	A1	10/2013	Gaddy
2011/0128412	A1	6/2011	Milnes et al.	2013/0265459	A1	10/2013	Duparre et al.
2011/0149408	A1	6/2011	Hahgholt et al.	2014/0009586	A1	1/2014	McNamer et al.
2011/0149409	A1	6/2011	Haugholt et al.	2014/0076336	A1	3/2014	Clayton et al.
2011/0153248	A1	6/2011	Gu et al.	2014/0079336	A1	3/2014	Venkataraman et al.
2011/0157321	A1	6/2011	Nakajima et al.	2014/0092281	A1	4/2014	Nisenzon et al.
2011/0176020	A1	7/2011	Chang	2014/0132810	A1	5/2014	McMahon
2011/0211824	A1	9/2011	Georgiev et al.	2014/0176592	A1	6/2014	Wilburn et al.
2011/0221599	A1	9/2011	Högasten	2014/0198188	A1	7/2014	Izawa
2011/0221658	A1	9/2011	Haddick et al.	2014/0218546	A1	8/2014	McMahon
2011/0221939	A1	9/2011	Jerdev	2014/0232822	A1	8/2014	Venkataraman et al.
2011/0234841	A1	9/2011	Akeley et al.	2014/0240528	A1	8/2014	Venkataraman et al.
2011/0241234	A1	10/2011	Duparre	2014/0240529	A1	8/2014	Venkataraman et al.
2011/0242342	A1	10/2011	Goma et al.	2014/0253738	A1	9/2014	Mullis
2011/0242355	A1	10/2011	Goma et al.	2014/0267243	A1	9/2014	Venkataraman et al.
2011/0242356	A1	10/2011	Aleksic et al.	2014/0267286	A1	9/2014	Duparre
2011/0255592	A1	10/2011	Sung et al.	2014/0267633	A1	9/2014	Venkataraman et al.
2011/0267348	A1	11/2011	Lin et al.	2014/0267762	A1	9/2014	Mullis et al.
2011/0273531	A1	11/2011	Ito et al.	2014/0267890	A1	9/2014	Lelescu et al.
2011/0274366	A1	11/2011	Tardif	2014/0285675	A1	9/2014	Mullis
2011/0279721	A1	11/2011	McMahon	2014/0321712	A1	10/2014	Ciurea et al.
2011/0285866	A1	11/2011	Bhrugumalla et al.	2014/0333731	A1	11/2014	Venkataraman et al.
2011/0298917	A1	12/2011	Yanagita	2014/0333764	A1	11/2014	Venkataraman et al.
2011/0300929	A1	12/2011	Tardif et al.	2014/0333787	A1	11/2014	Venkataraman et al.
2011/0310980	A1	12/2011	Mathew	2014/0340539	A1	11/2014	Venkataraman et al.
2011/0317766	A1	12/2011	Lim et al.	2014/0347509	A1	11/2014	Venkataraman et al.
2012/0012748	A1	1/2012	Pain et al.	2014/0347748	A1	11/2014	Duparre
2012/0026297	A1	2/2012	Sato	2014/0354773	A1	12/2014	Venkataraman et al.
2012/0026342	A1	2/2012	Yu et al.	2014/0354843	A1	12/2014	Venkataraman et al.
2012/0039525	A1	2/2012	Tian et al.	2014/0354844	A1	12/2014	Venkataraman et al.
2012/0044249	A1	2/2012	Mashitani et al.	2014/0354853	A1	12/2014	Venkataraman et al.
2012/0044372	A1	2/2012	Côté et al.	2014/0354854	A1	12/2014	Venkataraman et al.
2012/0069235	A1	3/2012	Imai	2014/0354855	A1	12/2014	Venkataraman et al.
2012/0113413	A1	5/2012	Miahczyłowicz-Wolski et al.	2014/0355870	A1	12/2014	Venkataraman et al.
2012/0147139	A1	6/2012	Li et al.	2014/0368662	A1	12/2014	Venkataraman et al.
2012/0147205	A1	6/2012	Lelescu et al.	2014/0368683	A1	12/2014	Venkataraman et al.
2012/0153153	A1	6/2012	Chang et al.	2014/0368684	A1	12/2014	Venkataraman et al.
2012/0154551	A1	6/2012	Inoue	2014/0368685	A1	12/2014	Venkataraman et al.
2012/0170134	A1	7/2012	Bolis et al.	2014/0368686	A1	12/2014	Duparre
2012/0176479	A1	7/2012	Mayhew et al.	2014/0369612	A1	12/2014	Venkataraman et al.
2012/0198677	A1	8/2012	Duparre	2014/0369615	A1	12/2014	Venkataraman et al.
2012/0200734	A1	8/2012	Tang	2014/0376825	A1	12/2014	Venkataraman et al.
2012/0218455	A1*	8/2012	Imai ..... G02B 13/001	2014/0376826	A1	12/2014	Venkataraman et al.
			348/340	2015/0003752	A1	1/2015	Venkataraman et al.
				2015/0003753	A1	1/2015	Venkataraman et al.
				2015/0009353	A1	1/2015	Venkataraman et al.



(56)

**References Cited**

## U.S. PATENT DOCUMENTS

2015/0009354 A1 1/2015 Venkataraman et al.  
 2015/0009362 A1 1/2015 Venkataraman et al.  
 2015/0015669 A1 1/2015 Venkataraman et al.

## FOREIGN PATENT DOCUMENTS

JP	2006033493	A	2/2006
JP	2007520107	A	7/2007
JP	2011109484	A	6/2011
JP	2013526801	A	6/2013
JP	2014521117	A	8/2014
WO	2007083579	A1	7/2007
WO	2008108271	A1	9/2008
WO	2009151903	A2	12/2009
WO	2011063347	A2	5/2011
WO	2011116203	A1	9/2011
WO	2011063347	A3	10/2011
WO	2011143501	A1	11/2011
WO	2012057619	A1	5/2012
WO	2012057620	A2	5/2012
WO	2012057621	A1	5/2012
WO	2012057622	A1	5/2012
WO	2012057623	A1	5/2012
WO	2012057620	A3	6/2012
WO	2012074361	A1	6/2012
WO	2012078126	A1	6/2012
WO	2012082904	A1	6/2012
WO	2012155119	A1	11/2012
WO	2013003276	A1	1/2013
WO	2013043751	A1	3/2013
WO	2013043761	A1	3/2013
WO	2013049699	A1	4/2013
WO	2013055960	A1	4/2013
WO	2013119706	A1	8/2013
WO	2013126578	A1	8/2013
WO	2014052974	A2	4/2014
WO	2014032020	A3	5/2014
WO	2014078443	A1	5/2014
WO	2014130849	A1	8/2014
WO	2014133974	A1	9/2014
WO	2014138695	A1	9/2014
WO	2014138697	A1	9/2014
WO	2014144157	A1	9/2014
WO	2014145856	A1	9/2014
WO	2014149403	A1	9/2014
WO	2014149902	A1	9/2014
WO	2014150856	A1	9/2014
WO	2014159721	A1	10/2014
WO	2014159779	A1	10/2014
WO	2014160142	A1	10/2014
WO	2014164550	A2	10/2014
WO	2014164909	A1	10/2014
WO	2014165244	A1	10/2014

## OTHER PUBLICATIONS

Nayar, "Computational Cameras: Redefining the Image", IEEE Computer Society, Aug. 2006, pp. 30-38.  
 Ng, "Digital Light Field Photography", Thesis, Jul. 2006, 203 pgs.  
 Ng et al., "Super-Resolution Image Restoration from Blurred Low-Resolution Images", Journal of Mathematical Imaging and Vision, 2005, vol. 23, pp. 367-378.  
 Nitta et al., "Image reconstruction for thin observation module by bound optics by using the iterative backprojection method", Applied Optics, May 1, 2006, vol. 45, No. 13, pp. 2893-2900.  
 Nomura et al., "Scene Collages and Flexible Camera Arrays", Proceedings of Eurographics Symposium on Rendering, 2007, 12 pgs.  
 Park et al., "Super-Resolution Image Reconstruction", IEEE Signal Processing Magazine, May 2003, pp. 21-36.  
 Pham et al., "Robust Super-Resolution without Regularization", Journal of Physics: Conference Series 124, 2008, pp. 1-19.  
 Polight, "Designing Imaging Products Using Reflowable Autofocus Lenses", <http://www.polight.no/tunable-polymer-autofocus-lens-html--11.html>.

Protter et al., "Generalizing the Nonlocal-Means to Super-Resolution Reconstruction", IEEE Transactions on Image Processing, Jan. 2009, vol. 18, No. 1, pp. 36-51.  
 Radtke et al., "Laser lithographic fabrication and characterization of a spherical artificial compound eye", Optics Express, Mar. 19, 2007, vol. 15, No. 6, pp. 3067-3077.  
 Rander et al., "Virtualized Reality: Constructing Time-Varying Virtual Worlds From Real World Events", Proc. of IEEE Visualization '97, Phoenix, Arizona, Oct. 19-24, 1997, pp. 277-283, 552.  
 Rhemann et al., "Fast Cost-Volume Filtering for Visual Correspondence and Beyond", IEEE Trans. Pattern Anal. Mach. Intell., 2013, vol. 35, No. 2, pp. 504-511.  
 Robertson et al., "Dynamic Range Improvement Through Multiple Exposures", In Proc. of the Int. Conf. on Image Processing, 1999, 5 pgs.  
 Robertson et al., "Estimation-theoretic approach to dynamic range enhancement using multiple exposures", Journal of Electronic Imaging, Apr. 2003, vol. 12, No. 2, pp. 219-228.  
 Roy et al., "Non-Uniform Hierarchical Pyramid Stereo for Large Images", Computer and Robot Vision, 2007, pp. 208-215.  
 Sauer et al., "Parallel Computation of Sequential Pixel Updates in Statistical Tomographic Reconstruction", ICIP 1995, pp. 93-96.  
 Seitz et al., "Plenoptic Image Editing", International Journal of Computer Vision 48, 2, pp. 115-129.  
 Shum et al., "Pop-Up Light Field: An Interactive Image-Based Modeling and Rendering System," Apr. 2004, ACM Transactions on Graphics, vol. 23, No. 2, pp. 143-162. Retrieved from [http://131.107.65.14/en-us/um/people/jiansun/papers/PopupLightField\\_TOG.pdf](http://131.107.65.14/en-us/um/people/jiansun/papers/PopupLightField_TOG.pdf) on Feb. 5.  
 Stollberg et al., "The Gabor superlens as an alternative wafer-level camera approach inspired by superposition compound eyes of nocturnal insects", Optics Express, Aug. 31, 2009, vol. 17, No. 18, pp. 15747-15759.  
 Sun et al., "Image Super-Resolution Using Gradient Profile Prior", Source and date unknown, 8 pgs.  
 Takeda et al., "Super-resolution Without Explicit Subpixel Motion Estimation", IEEE Transaction on Image Processing, Sep. 2009, vol. 18, No. 9, pp. 1958-1975.  
 Tanida et al., "Color imaging with an integrated compound imaging system", Optics Express, Sep. 8, 2003, vol. 11, No. 18, pp. 2109-2117.  
 Tanida et al., "Thin observation module by bound optics (TOMBO): concept and experimental verification", Applied Optics, Apr. 10, 2001, vol. 40, No. 11, pp. 1806-1813.  
 Taylor, "Virtual camera movement: The way of the future?", American Cinematographer 77, (Sep. 9), 93-100.  
 Vaish et al., "Reconstructing Occluded Surfaces Using Synthetic Apertures: Stereo, Focus and Robust Measures", Proceeding, CVPR '06 Proceedings of the 2006 IEEE Computer Society Conference on Computer Vision and Pattern Recognition—vol. 2, pp. 2331-2338.  
 Vaish et al., "Synthetic Aperture Focusing Using a Shear-Warp Factorization of the Viewing Transform", IEEE Workshop on A3DISS, CVPR, 2005, 8 pgs.  
 Vaish et al., "Using Plane + Parallax for Calibrating Dense Camera Arrays", IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 2004, 8 pgs.  
 Veilleux, "CCD Gain Lab: The Theory", University of Maryland, College Park-Observational Astronomy (ASTR 310), Oct. 19, 2006, pp. 1-5 (online), [retrieved on May 13, 2014]. Retrieved from the Internet <URL:[http://www.astro.umd.edu/~veilleux/ASTR310/fall06/ccd\\_theory.pdf](http://www.astro.umd.edu/~veilleux/ASTR310/fall06/ccd_theory.pdf), 5 pgs.  
 Vuong et al., "A New Auto Exposure and Auto White-Balance Algorithm to Detect High Dynamic Range Conditions Using CMOS Technology", Proceedings of the World Congress on Engineering and Computer Science 2008, WCECS 2008, Oct. 22-24, 2008.  
 Wang, "Calculation of Image Position, Size and Orientation Using First Order Properties", 10 pgs.  
 Wetzstein et al., "Computational Plenoptic Imaging", Computer Graphics Forum, 2011, vol. 30, No. 8, pp. 2397-2426.  
 Wheeler et al., "Super-Resolution Image Synthesis Using Projections Onto Convex Sets in the Frequency Domain", Proc. SPIE, 2005, 5674, 12 pgs.



(56)

## References Cited

## OTHER PUBLICATIONS

- Wikipedia, "Polarizing Filter (Photography)", [http://en.wikipedia.org/wiki/Polarizing\\_filter\\_\(photography\)](http://en.wikipedia.org/wiki/Polarizing_filter_(photography)), 1 pg.
- Wilburn, "High Performance Imaging Using Arrays of Inexpensive Cameras", Thesis of Bennett Wilburn, Dec. 2004, 128 pgs.
- Wilburn et al., "High Performance Imaging Using Large Camera Arrays", *ACM Transactions on Graphics*, Jul. 2005, vol. 24, No. 3, pp. 765-776.
- Wilburn et al., "High-Speed Videography Using a Dense Camera Array", *Proceeding, CVPR'04 Proceedings of the 2004 IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, pp. 294-301.
- Wilburn et al., "The Light Field Video Camera", *Proceedings of Media Processors 2002, SPIE Electronic Imaging, 2002*, 8 pgs.
- Wippermann et al., "Design and fabrication of a chirped array of refractive ellipsoidal micro-lenses for an apposition eye camera objective", *Proceedings of SPIE, Optical Design and Engineering II*, Oct. 15, 2005, 59622C-1-59622C-11.
- Yang et al., "A Real-Time Distributed Light Field Camera", *Eurographics Workshop on Rendering (2002)*, pp. 1-10.
- Yang et al., "Superresolution Using Preconditioned Conjugate Gradient Method", Source and date unknown, 8 pgs.
- Zhang et al., "A Self-Reconfigurable Camera Array", *Eurographics Symposium on Rendering, 2004*, 12 pgs.
- Zomet et al., "Robust Super-Resolution", *IEEE*, 2001, pp. 1-6.
- Bruckner et al., "Artificial compound eye applying hyperacuity", *Optics Express*, Dec. 11, 2006, vol. 14, No. 25, pp. 12076-12084.
- Bruckner et al., "Driving microoptical imaging systems towards miniature camera applications", *Proc. SPIE, Micro-Optics, 2010*, 11 pgs.
- Bruckner et al., "Thin wafer-level camera lenses inspired by insect compound eyes", *Optics Express*, Nov. 22, 2010, vol. 18, No. 24, pp. 24379-24394.
- Capel, "Image Mosaicing and Super-resolution", [online], Retrieved on Nov. 10, 2012. Retrieved from the Internet at URL:<<http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.226.2643&rep=rep1&type=pdf>>, Title pg., abstract, table of contents, pp. 1-263 (269 total pages).
- Chan et al., "Extending the Depth of Field in a Compound-Eye Imaging System with Super-Resolution Reconstruction", *Proceedings—International Conference on Pattern Recognition, 2006*, vol. 3, pp. 623-626.
- Chan et al., "Investigation of Computational Compound-Eye Imaging System with Super-Resolution Reconstruction", *IEEE, ISASSP 2006*, pp. 1177-1180.
- Chan et al., "Super-resolution reconstruction in a computational compound-eye imaging system", *Multidim Syst Sign Process*, 2007, vol. 18, pp. 83-101.
- Chen et al., "Interactive deformation of light fields", In *Proceedings of SIGGRAPH I3D 2005*, pp. 139-146.
- Drouin et al., "Fast Multiple-Baseline Stereo with Occlusion", *Proceedings of the Fifth International Conference on 3-D Digital Imaging and Modeling, 2005*, 8 pgs.
- Drouin et al., "Geo-Consistency for Wide Multi-Camera Stereo", *Proceedings of the 2005 IEEE Computer Society Conference on Computer Vision and Pattern Recognition, 2005*, 8 pgs.
- Drouin et al., "Improving Border Localization of Multi-Baseline Stereo Using Border-Cut", *International Journal of Computer Vision*, Jul. 2009, vol. 83, Issue 3, 8 pgs.
- Duparre et al., "Artificial apposition compound eye fabricated by micro-optics technology", *Applied Optics*, Aug. 1, 2004, vol. 43, No. 22, pp. 4303-4310.
- Duparre et al., "Artificial compound eye zoom camera", *Bioinspiration & Biomimetics*, 2008, vol. 3, pp. 1-6.
- Duparre et al., "Artificial compound eyes—different concepts and their application to ultra flat image acquisition sensors", *MOEMS and Miniaturized Systems IV, Proc. SPIE 5346*, Jan. 2004, pp. 89-100.
- Duparre et al., "Chirped arrays of refractive ellipsoidal microlenses for aberration correction under oblique incidence", *Optics Express*, Dec. 26, 2005, vol. 13, No. 26, pp. 10539-10551.
- Duparre et al., "Micro-optical artificial compound eyes", *Bioinspiration & Biomimetics*, 2006, vol. 1, pp. R1-R16.
- Duparre et al., "Microoptical artificial compound eyes—from design to experimental verification of two different concepts", *Proc. of SPIE, Optical Design and Engineering II*, vol. 5962, pp. 59622A-1-59622A-12.
- Duparre et al., "Microoptical Artificial Compound Eyes—Two Different Concepts for Compact Imaging Systems", *11th Microoptics Conference*, Oct. 30-Nov. 2, 2005, 2 pgs.
- Duparre et al., "Microoptical telescope compound eye", *Optics Express*, Feb. 7, 2005, vol. 13, No. 3, pp. 889-903.
- Duparre et al., "Micro-optically fabricated artificial apposition compound eye", *Electronic Imaging—Science and Technology, Prod. SPIE 5301*, Jan. 2004, pp. 25-33.
- Duparre et al., "Novel Optics/Micro-Optics for Miniature Imaging Systems", *Proc. of SPIE*, 2006, vol. 6196, pp. 619607-1-619607-15.
- Duparre et al., "Theoretical analysis of an artificial superposition compound eye for application in ultra flat digital image acquisition devices", *Optical Systems Design, Proc. SPIE 5249*, Sep. 2003, pp. 408-418.
- Duparre et al., "Thin compound-eye camera", *Applied Optics*, May 20, 2005, vol. 44, No. 15, pp. 2949-2956.
- Duparre et al., "Ultra-Thin Camera Based on Artificial Apposition Compound Eyes", *10th Microoptics Conference*, Sep. 1-3, 2004, 2 pgs.
- Fanaswala, "Regularized Super-Resolution of Multi-View Images", Retrieved on Nov. 10, 2012. Retrieved from the Internet at URL:<[http://www.site.uottawa.ca/~edubois/theses/Fanaswala\\_thesis.pdf](http://www.site.uottawa.ca/~edubois/theses/Fanaswala_thesis.pdf)>, 163 pgs.
- Farrell et al., "Resolution and Light Sensitivity Tradeoff with Pixel Size", *Proceedings of the SPIE Electronic Imaging 2006 Conference*, 2006, vol. 6069, 8 pgs.
- Farsiu et al., "Advances and Challenges in Super-Resolution", *International Journal of Imaging Systems and Technology*, 2004, vol. 14, pp. 47-57.
- Farsiu et al., "Fast and Robust Multiframe Super Resolution", *IEEE Transactions on Image Processing*, Oct. 2004, vol. 13, No. 10, pp. 1327-1344.
- Farsiu et al., "Multiframe Demosaicing and Super-Resolution of Color Images", *IEEE Transactions on Image Processing*, Jan. 2006, vol. 15, No. 1, pp. 141-159.
- Feris et al., "Multi-Flash Stereopsis: Depth Edge Preserving Stereo with Small Baseline Illumination", *IEEE Trans on PAMI*, 2006, 31 pgs.
- Fife et al., "A 3D Multi-Aperture Image Sensor Architecture", *Custom Integrated Circuits Conference, 2006, CICC '06, IEEE*, pp. 281-284.
- Fife et al., "A 3MPixel Multi-Aperture Image Sensor with 0.7 $\mu$ m Pixels in 0.11 $\mu$ m CMOS", *ISSCC 2008, Session 2, Image Sensors & Technology*, 2008, pp. 48-50.
- Fischer et al., *Optical System Design, 2nd Edition*, SPIE Press, pp. 191-198.
- Fischer et al., *Optical System Design, 2nd Edition*, SPIE Press, pp. 49-58.
- Goldman et al., "Video Object Annotation, Navigation, and Composition", In *Proceedings of UIST 2008*, pp. 3-12.
- Gortler et al., "The Lumigraph", In *Proceedings of SIGGRAPH 1996*, pp. 43-54.
- Hacohen et al., "Non-Rigid Dense Correspondence with Applications for Image Enhancement", *ACM Transactions on Graphics*, 30, 4, 2011, pp. 70:1-70:10.
- Hamilton, "JPEG File Interchange Format, Version 1.02", Sep. 1, 1992, 9 pgs.
- Hardie, "A Fast Image Super-Algorithm Using an Adaptive Wiener Filter", *IEEE Transactions on Image Processing*, Dec. 2007, vol. 16, No. 12, pp. 2953-2964.
- Hasinoff et al., "Search-and-Replace Editing for Personal Photo Collections", *Computational Photography (ICCP) 2010*, pp. 1-8.
- Horisaki et al., "Irregular Lens Arrangement Design to Improve Imaging Performance of Compound-Eye Imaging Systems", *Applied Physics Express*, 2010, vol. 3, pp. 022501-1-022501-3.



(56)

**References Cited**

## OTHER PUBLICATIONS

Horisaki et al., "Superposition Imaging for Three-Dimensionally Space-Invariant Point Spread Functions", *Applied Physics Express*, 2011, vol. 4, pp. 112501-1-112501-3.

Horn et al., "LightShop: Interactive Light Field Manipulation and Rendering", In *Proceedings of I3D 2007*, pp. 121-128.

Isaksen et al., "Dynamically Reparameterized Light Fields", In *Proceedings of SIGGRAPH 2000*, pp. 297-306.

Jarabo et al., "Efficient Propagation of Light Field Edits", in *Proceedings of SIACG 2011*, pp. 75-80.

Joshi et al., "Synthetic Aperture Tracking: Tracking Through Occlusions", *I CCV IEEE 11th International Conference on Computer Vision*; Publication [online]. Oct. 2007 [retrieved Jul. 28, 2014]. Retrieved from the Internet: <URL:http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4409032&isnumber=4408819>; pp. 1-8.

Kang et al., "Handling Occlusions in Dense Multi-View Stereo", *Computer Vision and Pattern Recognition*, 2001, vol. 1, pp. I-103-I-110.

Kitamura et al., "Reconstruction of a high-resolution image on a compound-eye image-capturing system", *Applied Optics*, Mar. 10, 2004, vol. 43, No. 8, pp. 1719-1727.

Krishnamurthy et al., "Compression and Transmission of Depth Maps for Image-Based Rendering", *Image Processing*, 2001, pp. 828-831.

Kutulakos et al., "Occluding Contour Detection Using Affine Invariants and Purposive Viewpoint Control", *Proc., CVPR 94*, 8 pgs.

Lensvector, "How LensVector Autofocus Works", printed Nov. 2, 2012 from <http://www.lensvector.com/overview.html>, 1 pg.

Levoy, "Light Fields and Computational Imaging", *IEEE Computer Society*, Aug. 2006, pp. 46-55.

Levoy et al., "Light Field Rendering", *Proc. ACM SIGGRAPH '96*, pp. 1-12.

Li et al., "A Hybrid Camera for Motion Deblurring and Depth Map Super-Resolution," Jun. 23-28, 2008, *IEEE Conference on Computer Vision and Pattern Recognition*, 8 pgs. Retrieved from [www.eecis.udel.edu/~jye/lab\\_research/08/deblur-feng.pdf](http://www.eecis.udel.edu/~jye/lab_research/08/deblur-feng.pdf) on Feb. 5, 2014.

Liu et al., "Virtual View Reconstruction Using Temporal Information", 2012 *IEEE International Conference on Multimedia and Expo*, 2012, pp. 115-120.

Lo et al., "Stereoscopic 3D Copy & Paste", *ACM Transactions on Graphics*, vol. 29, No. 6, Article 147, Dec. 2010, pp. 147:1-147:10. International Preliminary Report on Patentability for International Application No. PCT/US2012/059813, Search Completed Apr. 15, 2014, 7 pgs.

International Preliminary Report on Patentability for International Application PCT/US2013/024987, Mailed Aug. 21, 2014, 13 Pgs.

International Preliminary Report on Patentability for International Application PCT/US2013/027146, Report Completed Apr. 2, 2013, Report Issued Aug. 26, 2014, 10 pages.

International Preliminary Report on Patentability for International Application PCT/US2013/039155, completed Nov. 4, 2014, Mailed Nov. 13, 2014, 10 Pgs.

International Preliminary Report on Patentability for International Application PCT/US2013/046002, Report completed Dec. 31, 2014, Mailed Jan. 8, 2015, 6 Pgs.

International Preliminary Report on Patentability for International Application PCT/US2013/048772, Report completed Dec. 31, 2014, Mailed Jan. 8, 2015, 8 Pgs.

International Search Report and Written Opinion for International Application No. PCT/US13/46002, Search completed Nov. 13, 2013, Mailed Nov. 29, 2013, 7 pgs.

International Search Report and Written Opinion for International Application No. PCT/US13/56065, Search Completed Nov. 25, 2013, Mailed Nov. 26, 2013, 8 pgs.

International Search Report and Written Opinion for International Application No. PCT/US13/59991, Completed Feb. 6, 2014, Mailed Feb. 26, 2014, 8 pgs.

International Search Report and Written Opinion for International Application No. PCT/US2009/044687, completed Jan. 5, 2010, date mailed Jan. 13, 2010, 9 pgs.

International Search Report and Written Opinion for International Application No. PCT/US2011/64921, Report Completed Feb. 25, 2011, mailed Mar. 6, 2012, 17 pgs.

International Search Report and Written Opinion for International Application No. PCT/US2013/024987, Completed Mar. 27, 2013, Mailed Apr. 15, 2013, 14 pgs.

International Search Report and Written Opinion for International Application No. PCT/US2013/027146, completed Apr. 2, 2013, 12 pgs.

International Search Report and Written Opinion for International Application No. PCT/US2013/048772, Search Completed Oct. 21, 2013, Mailed Nov. 8, 2013, 6 pgs.

International Search Report and Written Opinion for International Application No. PCT/US2013/056502, Completed Feb. 18, 2014, Mailed Mar. 19, 2014, 7 pgs.

International Search Report and Written Opinion for International Application No. PCT/US2013/069932, Search Completed Mar. 14, 2014, Mailed Apr. 14, 2014, 12 pgs.

International Search Report and Written Opinion for International Application PCT/US11/36349, mailed Aug. 22, 2011, 11 pgs.

International Search Report and Written Opinion for International Application PCT/US13/62720, report completed Mar. 25, 2014, Mailed Apr. 21, 2014, 9 Pgs.

International Search Report and Written Opinion for International Application PCT/US14/024903 report completed Jun. 12, 2014, Mailed, Jun. 27, 2014, 13 pgs.

International Search Report and Written Opinion for International Application PCT/US14/17766, report completed May 28, 2014, 9 Pgs.

International Search Report and Written Opinion for International Application PCT/US14/18084, completed May 23, 2014, Mailed Jun. 10, 2014, 12 Pgs.

International Search Report and Written Opinion for International Application PCT/US14/18116, Report completed May 13, 2014, 12 pgs.

International Search Report and Written Opinion for International Application PCT/US14/22118, report completed Jun. 9, 2014, Mailed Jun. 25, 2014, 5 pgs.

International Search Report and Written Opinion for International Application PCT/US14/22774 report completed Jun. 9, 2014, Mailed Jul. 14, 2014, 6 Pgs.

International Search Report and Written Opinion for International Application PCT/US14/24407, report completed Jun. 11, 2014, Mailed Jul. 8, 2014, 9 Pgs.

International Search Report and Written Opinion for International Application PCT/US14/25100, report completed Jul. 7, 2014, Mailed Aug. 7, 2014 5 Pgs.

International Search Report and Written Opinion for International Application PCT/US14/25904 report completed Jun. 10, 2014, Mailed Jul. 10, 2014, 6 Pgs.

International Search Report and Written Opinion for International Application PCT/US2010/057661, completed Mar. 9, 2011, 14 pgs.

International Search Report and Written Opinion for International Application PCT/US2012/044014, completed Oct. 12, 2012, 15 pgs.

International Search Report and Written Opinion for International Application PCT/US2012/056151, completed Nov. 14, 2012, 10 pgs.

International Search Report and Written Opinion for International Application PCT/US2012/059813, Report completed Dec. 17, 2012, 8 pgs.

International Search Report and Written Opinion for International Application PCT/US2012/37670, Mailed Jul. 18, 2012, completed Jul. 5, 2012, 9 pgs.

International Search Report and Written Opinion for International Application PCT/US2012/58093, Report completed Nov. 15, 2012, 12 pgs.

International Search Report and Written Opinion for International Application PCT/US2014/022123, completed Jun. 9, 2014, Mailed Jun. 25, 2014, 5 pgs.

International Search Report and Written Opinion for International Application PCT/US2014/024947, completed Jul. 8, 2014, Mailed Aug. 5, 2014, 8 Pgs.



(56)

**References Cited**

## OTHER PUBLICATIONS

International Search Report and Written Opinion for International Application PCT/US2014/028447, completed Jun. 30, 2014, Mailed Jul. 21, 2014, 8 Pgs.

International Search Report and Written Opinion for International Application PCT/US2014/030692, completed Jul. 28, 2014, Mailed Aug. 27, 2014, 7 Pages.

International Search Report and Written Opinion for International Application PCT/US2014/23762, Completed May 30, 2014, Mailed Jul. 3, 2014, 6 Pgs.

International Search Report and Written Opinion for International Application PCT/US14/21439, completed Jun. 5, 2014, Mailed Jun. 20, 2014, 10 Pgs.

Office Action for U.S. Appl. No. 12/952,106, dated Aug. 16, 2012, 12 pgs.

Baker et al., "Limits on Super-Resolution and How to Break Them", IEEE Transactions on Pattern Analysis and Machine Intelligence, Sep. 2002, vol. 24, No. 9, pp. 1167-1183.

Bertero et al., "Super-resolution in computational imaging", Micron, 2003, vol. 34, Issues 6-7, 17 pgs.

Bishop et al., "Full-Resolution Depth Map Estimation from an Aliased Plenoptic Light Field", ACCV 2010, Part II, LNCS 6493, pp. 186-200.

Bishop et al., "Light Field Superresolution", Retrieved from <http://home.eps.hw.ac.uk/~sz73/ICCP09/LightFieldSuperresolution.pdf>, 9 pgs.

Bishop et al., "The Light Field Camera: Extended Depth of Field, Aliasing, and Superresolution", IEEE Transactions on Pattern Analysis and Machine Intelligence, May 2012, vol. 34, No. 5, pp. 972-986.

Borman, "Topics in Multiframe Superresolution Restoration", Thesis of Sean Borman, Apr. 2004, 282 pgs.

Borman et al., "Image Sequence Processing", Source unknown, Oct. 14, 2002, 81 pgs.

Borman et al., "Block-Matching Sub-Pixel Motion Estimation from Noisy, Under-Sampled Frames—An Empirical Performance Evaluation", Proc SPIE, Dec. 1998, 3653, 10 pgs.

Borman et al., "Image Resampling and Constraint Formulation for Multi-Frame Super-Resolution Restoration", Proc. SPIE, Jun. 2003, 5016, 12 pgs.

Borman et al., "Linear models for multi-frame super-resolution restoration under non-affine registration and spatially varying PSF", Proc. SPIE, May 2004, vol. 5299, 12 pgs.

Borman et al., "Nonlinear Prediction Methods for Estimation of Clique Weighting Parameters in NonGaussian Image Models", Proc. SPIE, 1998, 3459, 9 pgs.

Borman et al., "Simultaneous Multi-Frame MAP Super-Resolution Video Enhancement Using Spatio-Temporal Priors", Image Processing, 1999, ICIP 99 Proceedings, vol. 3, pp. 469-473.

Borman et al., "Super-Resolution from Image Sequences—A Review", Circuits & Systems, 1998, pp. 374-378.

Bose et al., "Superresolution and Noise Filtering Using Moving Least Squares", IEEE Transactions on Image Processing, date unknown, 21 pgs.

Boye et al., "Comparison of Subpixel Image Registration Algorithms", Proc. of SPIE-IS&T Electronic Imaging, vol. 7246, pp. 72460X-1-72460X-9.

\* cited by examiner



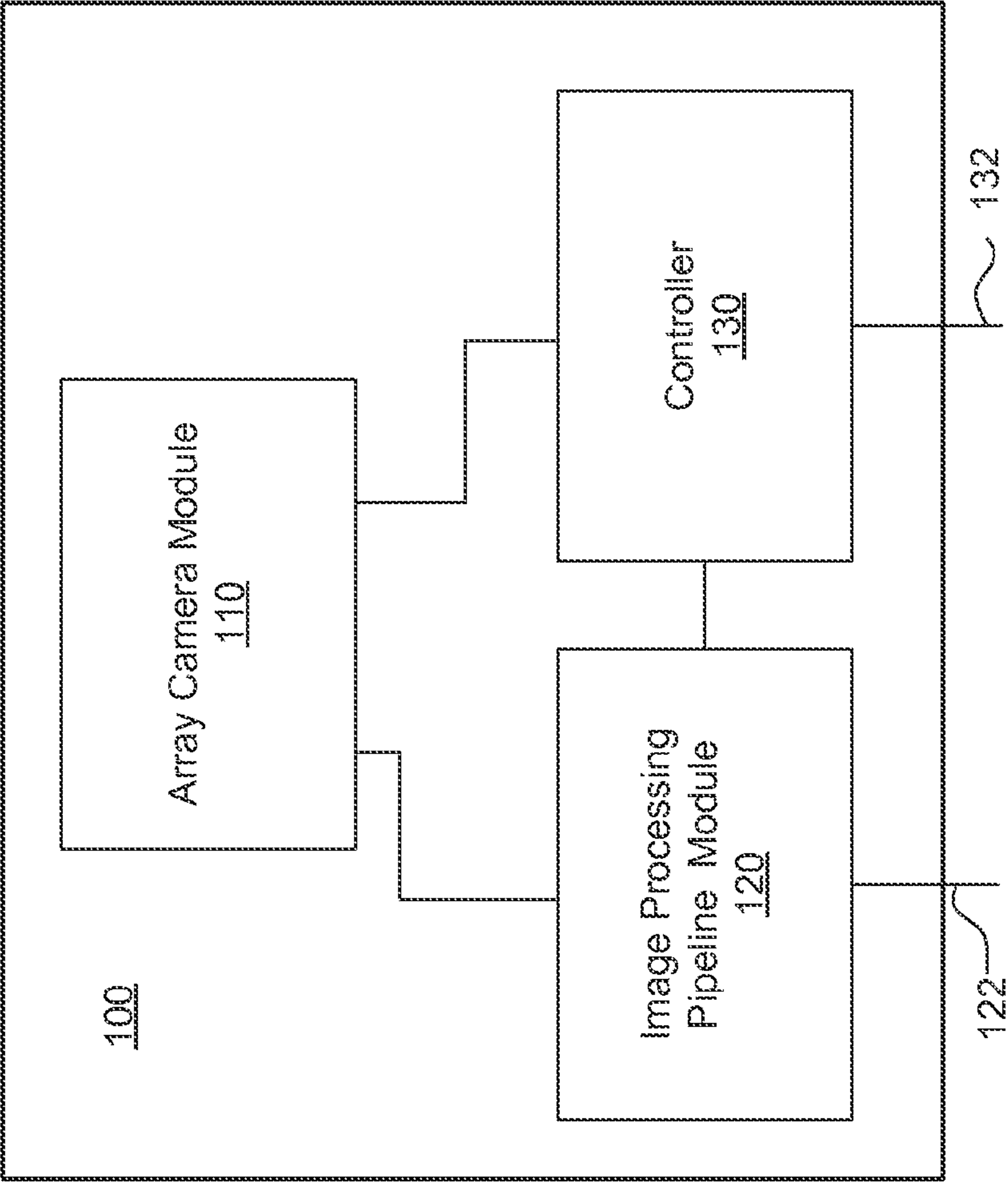


FIG. 1



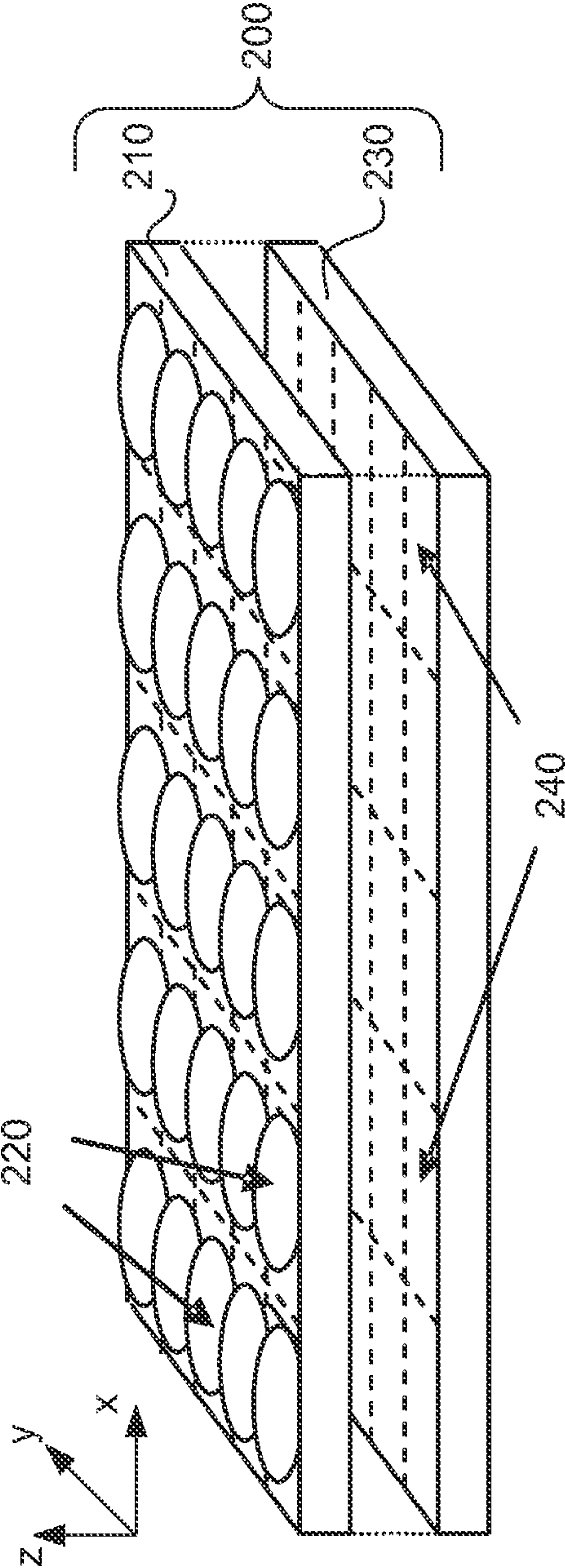


FIG. 2



G	B	G
R	G	R
G	B	G

FIG. 3



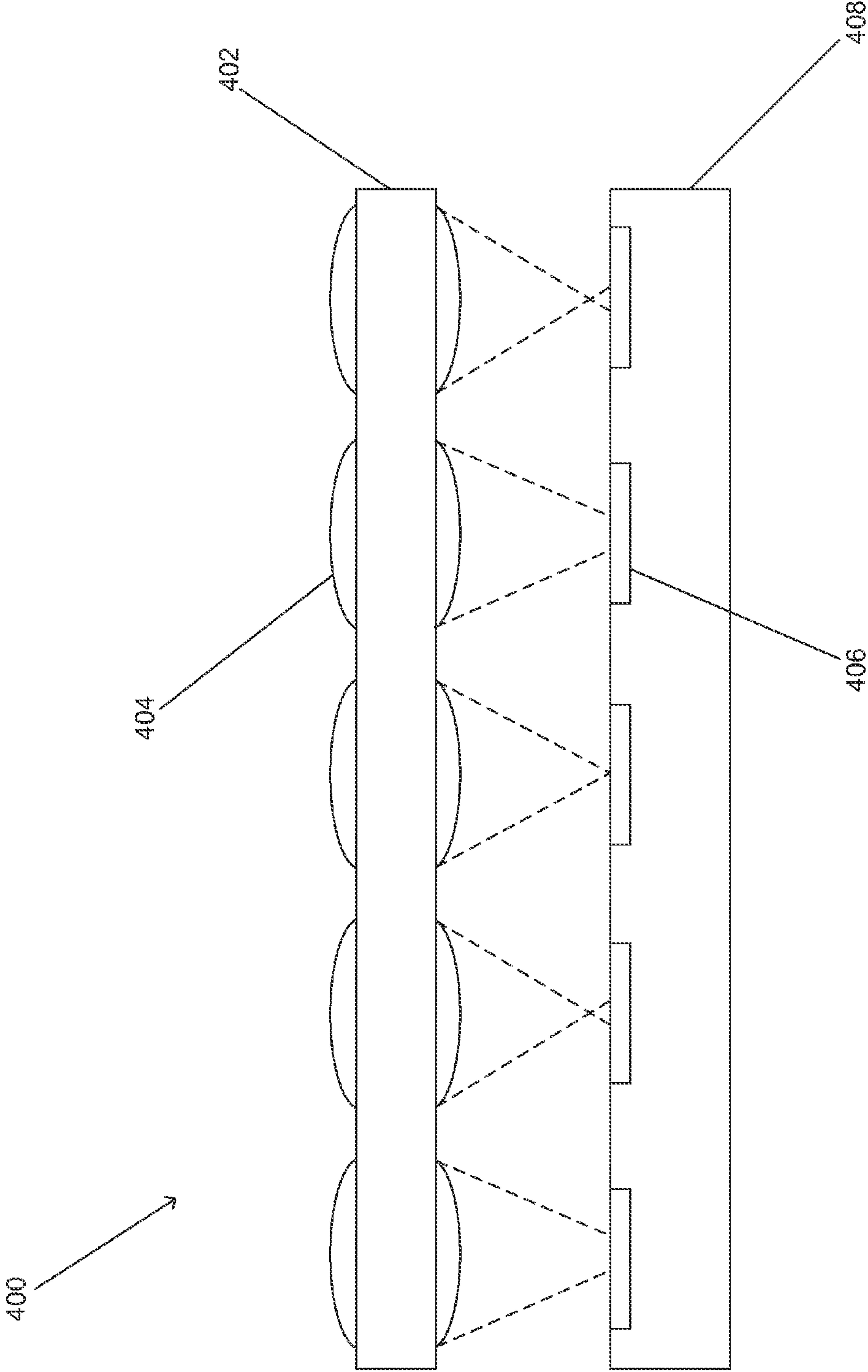


FIG. 4



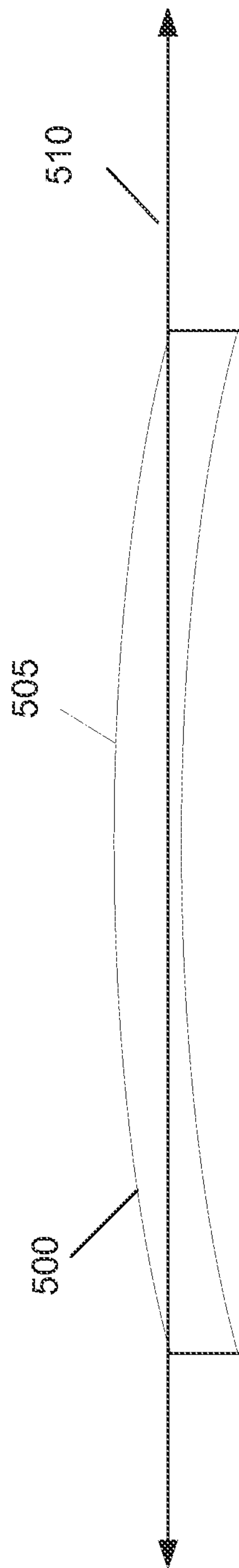


FIG. 5



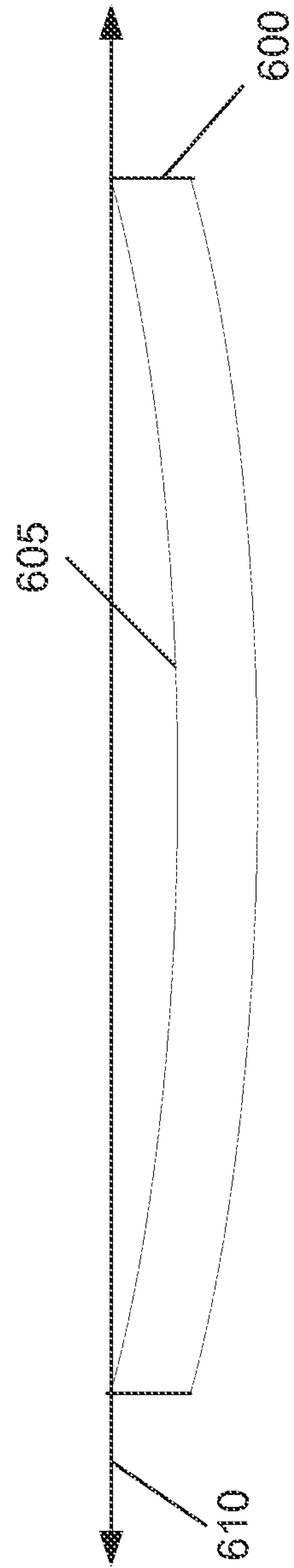


FIG. 6

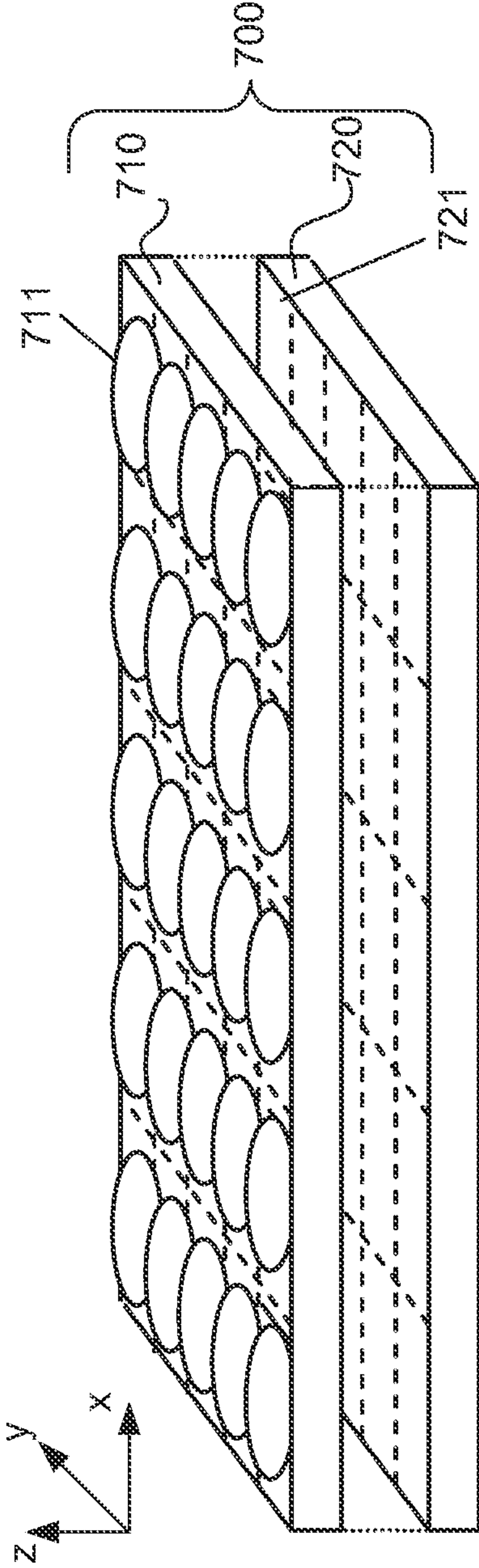


FIG. 7



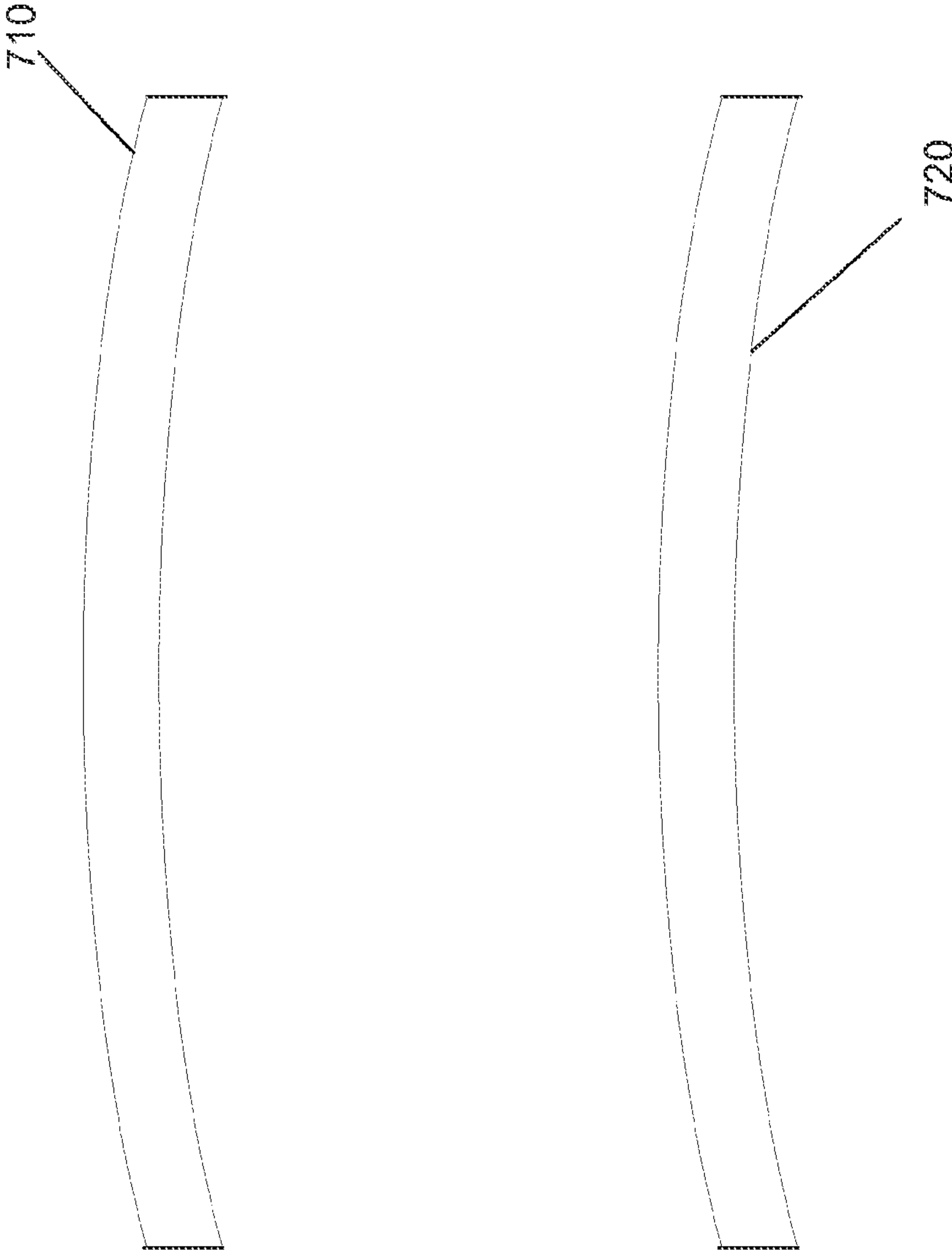


FIG. 8

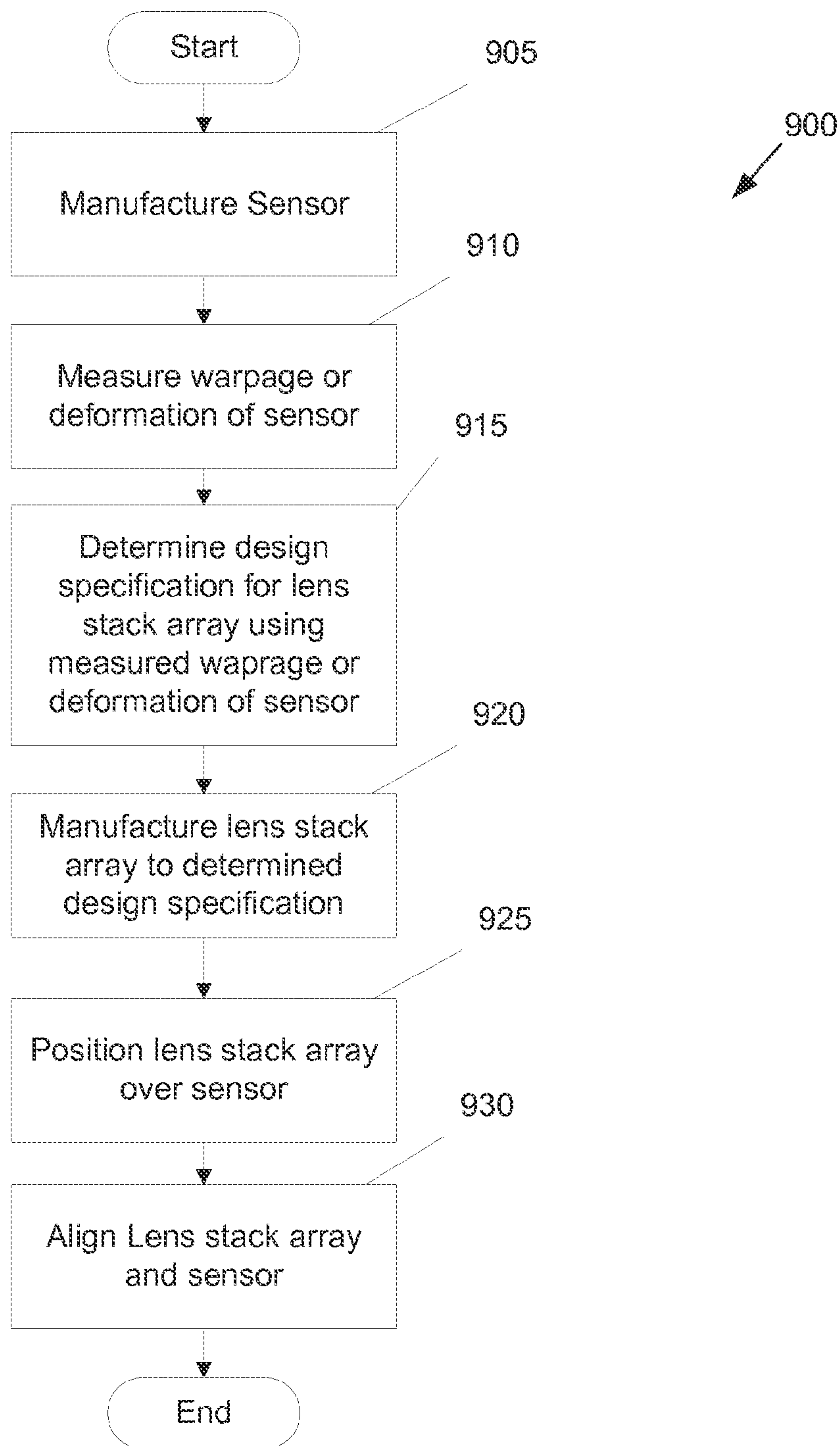


FIG. 9



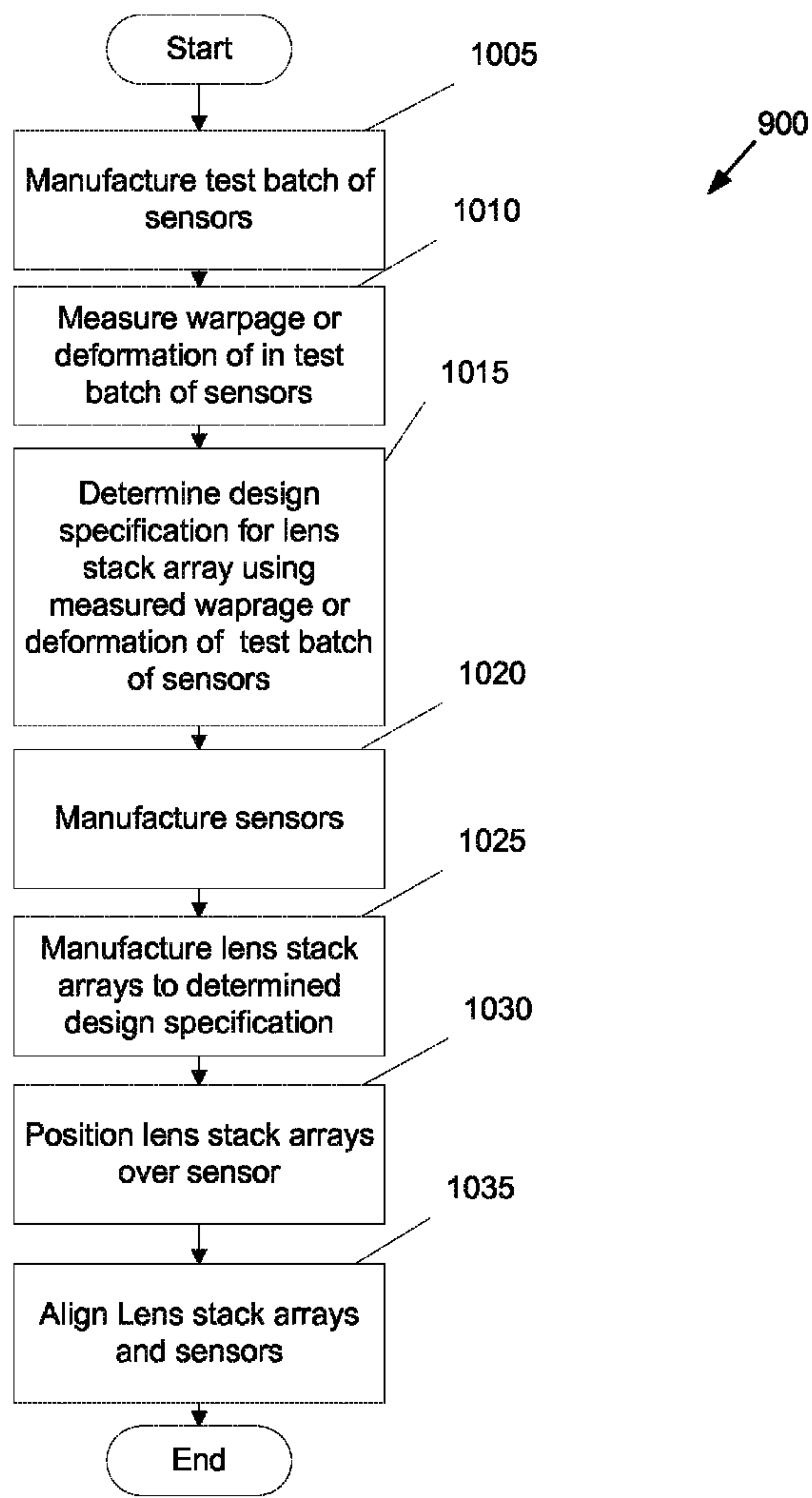


FIG. 10

1

**SYSTEMS AND METHODS FOR  
CORRECTING FOR WARPAGE OF A SENSOR  
ARRAY IN AN ARRAY CAMERA MODULE  
BY INTRODUCING WARPAGE INTO A  
FOCAL PLANE OF A LENS STACK ARRAY**

CROSS-REFERENCE TO RELATED  
APPLICATION

The present invention claims priority under 35 U.S.C. §119 (e) to U.S. Provisional Patent Application Ser. No. 61/976,335 entitled "Sensor Array Warpage Compensation by Intentionally Introducing Warpage into the Lens Array", filed Apr. 7, 2014, the disclosure of which is incorporated by reference herein in its entirety.

FIELD OF THE INVENTION

The present invention generally relates to reducing the variation of the back focal length of lens in a lens stack array of an array camera module.

BACKGROUND

In response to the constraints placed upon a traditional digital camera based upon the camera obscura, a new class of cameras that can be referred to as array cameras has been proposed. Array cameras are characterized in that they include an imager array, or sensor, that has multiple arrays of pixels, where each pixel array is intended to define a focal plane, and each focal plane has a separate lens stack. Typically, each focal plane includes a plurality of rows of pixels that also forms a plurality of columns of pixels, and each focal plane is contained within a region of the imager that does not contain pixels from another focal plane. An image is typically formed on each focal plane by its respective lens stack. In many instances, the array camera is constructed using an imager array that incorporates multiple focal planes and an optic array of lens stacks.

SUMMARY OF THE INVENTION

An advance in the art is by systems and methods for correcting warpage of a sensor array in an array camera module by introducing warpage into a projection plane of images formed by the lens stack in accordance with at least some embodiments of this invention. In accordance with some embodiments of the invention, an array camera includes an array camera module. The array camera module includes a sensor and a lens stack array. The sensor includes an array of pixels that is subdivided into a sub-arrays of pixels and each of the sub-arrays forms a focal plane. The lens stack array includes a set of lens stacks. Each of lens stacks includes an aperture and forms an image on a focal plane formed by one of the sub-array of pixels on the sensor. The surface of the sensor on which images are formed includes a warpage and a projection plane of images formed by the lens stack array incorporates a warpage that at least partially corrects the warpage in the sensor.

In accordance with some embodiments, the warpage of the sensor has a curvature of a bow that is convex. In accordance with some embodiments, the warpage of the focal plane of the lens stack array has a curvature of a bow that is convex.

In accordance with many embodiments, the curvature of the warpage of the focal of the lens stack array is substantially equal to the curvature of the warpage of the sensor.

2

In accordance with some embodiments, the warpage of the lens stack array corrects the warpage of the sensor to provide back focal lengths for each of the lens stacks in the lens stack array that are substantially consistent.

In accordance with some embodiments, a method of manufacturing array cameras that correct for warpage in a sensor array with warpage in the focal plane of a lens stack is performed in the following manner. A first set of sensors for camera arrays are manufactured. Each of the sensors includes an array of pixels that is subdivided into of sub-arrays of pixels and each of the sub-arrays forms a focal plane. The warpage in each of the sensors manufactured is measured and used to generate warpage information. A lens stack array comprising a set of lens stacks where each of the lens stacks is associated with a focal plane formed by one of the sub-arrays of pixels in the sensor is designed based upon the warpage information. The designed lens stack array is configured to have a projection plane of images formed by the lens stack array that has a warpage that corrects the warpage in the sensor. A second set of sensors is manufactured and a lens stack arrays are manufactured in accordance with the design. The lens stack are then placed over the sensor to form and array camera module.

In accordance with some embodiments the lens stacks in each of the stack arrays is aligned with focal planes formed by the plurality of sub-arrays in each of the second set of sensors. In accordance with a number of embodiments, the warpage in the lens stack array design corrects the warpage of the first set of sensors to provide back focal lengths for each of the lens stacks in the lens stack array that are substantially consistent when placed over the second set of sensors.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 conceptually illustrates an array camera in accordance with an embodiment of the invention.

FIG. 2 illustrates an array camera module in accordance with an embodiment of the invention.

FIG. 3 illustrates an array camera module that employs a  $\pi$  filter in accordance with an embodiment of the invention.

FIG. 4 conceptually illustrates variations in focal length that can occur during the manufacture of an array camera module using a lens stack array and a sensor in accordance with embodiments of the invention.

FIG. 5 conceptually illustrates a convex warpage of a sensor of an array camera in accordance with embodiments of this invention.

FIG. 6 conceptually illustrates a concave warpage of a sensor of an array camera in accordance with embodiments of this invention.

FIG. 7 conceptually illustrates a lens stack array aligned over a sensor in accordance with an embodiment of this invention.

FIG. 8 conceptually illustrates a lens stack array that is designed with a projection plane that has a warpage that is substantially equal to the warpage in a warped sensor in accordance with an embodiment of this invention.

FIG. 9 illustrates a flow diagram of a process for manufacturing an array camera with a lens stack array that is designed with a warpage that is opposite the warpage in a warped sensor in accordance with an embodiment of this invention.

FIG. 10 illustrates a flow diagram of a process for mass manufacture of an array camera with a lens stack array that is designed with a warpage that is opposite the warpage in a warped or deformed sensor in accordance with an embodiment of this invention.



## DETAILED DESCRIPTION

Turning now to the drawings, systems and methods for correcting warpage of a sensor of an array camera module by introducing warpage into a lens stack array in accordance with embodiments of the invention are illustrated. Processes for constructing array camera modules using lens stack arrays are described in U.S. Patent Publication No. 20011/0069189, entitled “Capturing and Processing of Images Using Monolithic Camera Array with Heterogeneous Imagers”, Venkataraman et al. The disclosure of U.S. Patent Publication No. 20011/0069189 is incorporated by reference herein in its entirety. The monolithic array camera modules illustrated in U.S. Patent Publication No. 20011/0069189 can be constructed from an optic array of lens stacks, also termed a ‘lens stack array’, where each lens stack in the array defines an optical channel, and where the lens stack array is associated with a monolithic imager array, or ‘sensor’, including a plurality of focal planes corresponding to the optical channels in the lens stack array. Each focal plane can include a plurality of rows of pixels that also forms a plurality of columns of pixels, and each focal plane may be contained within a region of the imager array that does not contain pixels from another focal plane. An image may be formed on each focal plane by a respective lens stack. The combination of a lens stack array and a sensor can be understood to be an ‘array camera module’ and the combination of an individual lens stack and its corresponding focal plane within the sensor can be understood to be a ‘camera.’ Ideally, the lens stack array of an array camera is constructed so that each lens stack within it has the same focal length. However, the large number of tolerances involved in the manufacture of a lens stack array can result in the different lens stacks having varying focal lengths. The combination of all the manufacturing process variations typically results in a deviation of the actual (“first order”) lens parameters—such as focal length—from the nominal prescription. As a result, each lens stack can have a different axial optimum image location. And consequently, since the sensor is monolithic, it typically cannot be placed a distance that corresponds with the focal length of each camera within an array camera module. There are a variety of processes in the manufacturing of conventional camera modules that can be utilized to align a lens stack array with a sensor to achieve acceptable imaging performance including active alignment processes and passive alignment processes.

One particular problem that arises during manufacture is that the lens stack array and/or the sensor may not be sufficiently flat when the components are combined into an array camera module. If either the lens stack array (or more particularly, the projection plane of the images projected from the lens stack) and/or the sensor are warped, the individual lens stacks may be misaligned with the desired focal planes when the lens stack array is affixed to the sensor causing varying focusing problems to arise. The sensor may be warped due to many factors, including, but not limited to, mismatch issues of the Coefficient of Thermal Expansion (CTE) of material of the sensor and of the Printed Circuit Board (PCB) during the attachment process in which the components are subjects to elevated curing temperatures. The lens stack array (or more particularly, the projection plane of the images projected from the lens stack) may be warped due to factors including, but not limited, manufacturing defects in the lens stack arrays and the stress induced by placement of the lens stack into a holder over the sensor. Although much of the discussion that follows refers to sensor warpage, the techniques described herein can be equally applied to correct any form of sensor deformation as appropriate to the require-

ments of specific manufacturing processes in accordance with embodiments of the invention.

The warpage of the lens stack array and/or the sensor may cause the distance and/or angle between the individual lens stacks and individual pixel arrays in the sensor to vary. This variation in distance and/or angle may cause a back focal length variation of the individual lens in the lens array over the focal planes on the sensor array of the array camera that is referred to as warpage of the projection plane of the lens stack where the projection plane is the plane in which the images are focused. Typically, the curvature sign of the bow of the warpage of the sensor is convex while the curvature sign of the bow of the warpage of the projection plane of the lens stack array may vary between convex and concave. Commonly, the only way to minimize back focal length variations is to minimize the warpage in between the projection plane of the lens stack and the sensor prior to alignment.

In accordance with some embodiments of this invention, the variations in the back focal lengths of the individual lens stacks in the lens stack array are reduced by matching the warpage of the sensor and the warpage in the projection plane of lens stack array such that the warpage in the projection plane of the lens stack array corrects for the warpage of the sensor. In accordance with some embodiments, the warpage may be corrected by forming the components such that the curvature sign of the bows for each component are substantially equal to one another. In accordance with some other embodiments, the warpage in the sensor may be corrected by varying the BFL of individual lens stacks in the lens stack array such that the curvature sign of the warpage of the projection plane is substantially equal to the curvature sign of the warpage of the sensor. The equality of the curvature signs of the deformation in the sensor and the projection plane of the lens stacks results in a defocusing pattern in the array camera that is substantially free of the bow. The variation in the resulting Back Focal Length (BFL) pattern of the array camera module is decreased relative to an array camera module manufactured using a planar lens stack array (i.e. a lens stack array manufactured to minimize warpage).

In accordance with some embodiments of the invention, the process for manufacturing an array camera module includes manufacturing and/or packaging a sensor without enforcing a flatness requirement. The warpage of the manufactured sensor can be measured to determine warpage information for the sensor. The warpage information for the sensor can be used to design a lens stack array with a warpage in the projection plane that corrects for the warpage in the sensor. In accordance with some embodiments, the warpage in the sensor is corrected by having a warpage in the lens stack array that has a bow curvature sign that is substantially equal to the bow curvature sign of the manufactured sensor array. In accordance with some other embodiments, the warpage in the sensor may be corrected by varying the BFL of individual lens stacks in the lens stack array such that the curvature sign of the warpage of the focal plane is substantially equal to the curvature sign of the warpage of the sensor. Conventional alignment and assembly processes can then be used to align the lens stack relative to the sensor and form an array camera module.

A process for manufacturing individual lens array stacks for each sensor array would costly and time consuming. Furthermore, while the magnitude of warpage observed in the sensor may be significant. For example the warpage may be as much as 25  $\mu\text{m}$ . However, the variation of the warpage between sensors arrays manufactured in the same manufacturing lot is typically less than 5  $\mu\text{m}$  and is more typically on the order of 3  $\mu\text{m}$ . Thus, a process for matching the warpage



of a lot of produced lens stack arrays to warpage in a lot of manufactured sensors arrays may be performed in accordance with embodiments of this invention to reduce the BFL-variation in mass produced array camera modules. In some embodiments of this invention, the process includes manufacturing a group of sensors in an array using a standard process without enforcing flatness requirements. The warpage of each of the produced sensors in the group are then measured to generate warpage information. In accordance with some embodiments the warpage information may include an average bow curvature sign of the group of sensors. The warpage information of the group of sensors is then used to design a lens stack arrays with warpage of the array image surface that corrects for the warpage in sensors. In accordance with some embodiments, the lens stack array design has a bow curvature sign that is substantially equal to the bow curvature sign of the warpage in the group of sensors. Lens stack arrays can then be manufactured in accordance with the design and additional sensors can be manufactured in accordance with the process used to manufacture the initial group of sensors that formed the basis of the lens stack array design. Conventional alignment and assembly processes can then be used to form array camera modules from the lens stack arrays and sensors. The resulting array camera modules can have reduced BFL-variation relative to array camera modules manufactured without modifying the design of the lens stack arrays based upon the measured warpage of the initial group of sensors. In many instances, designing the lens stack array considering measured sensor warpage can increase array camera module yield and provide reductions in manufacturing costs.

Alignment of sensors and lens stack arrays may be performed using active/or passive alignment. In the context of the manufacture of camera systems, the term active alignment typically refers to a process for aligning an optical component or element (e.g. a lens stack array) with an image receiving component or element (e.g. a monolithic sensor) to achieve a final desirable spatial arrangement by evaluating the efficacy of the image receiving component's ability to capture and record images as a function of the spatial relationship between the optical component and the image receiving component, and using this evaluation information to assist in the alignment process. Processes for actively aligning a lens stack array with an array of focal planes are described in U.S. Patent Publication No. 2014/0002674, entitled "Systems and Methods for Manufacturing Camera Modules Using Active Alignment of Lens Stack Arrays and Sensors", Duparre et al. The disclosure of U.S. Patent Application Publication No. 2014/0002674 is incorporated by reference herein in its entirety.

Ideally, when manufacturing camera modules in bulk, each camera module would be individually assembled using a rigorous assembly process, such as an active alignment process, to provide a quality configuration. However, performing such processes in bulk may be costly and time-consuming. An alternative to the use of an active alignment process to manufacture camera modules is the use of a passive alignment process. The term passive alignment typically refers to aligning an optical system with an imaging system to achieve a final desirable spatial arrangement using predetermined configuration parameters (e.g., the spacing between the lens stack array and the sensor is predetermined). Processes for utilizing alignment information obtained during active alignment of one or more representative lens stack arrays and sensors to form array camera modules to manufacture array camera modules using passive alignment processes are disclosed in U.S. patent application Ser. No. 14/195,675 entitled "Passive

Alignment of Array Camera Modules Constructed from Lens Stack Arrays and Sensors Based Upon Alignment Information Obtained During Manufacture of Array Camera Modules Using an Active Alignment Process" to Duparre et al. The disclosure of U.S. patent application Ser. No. 14/195,675 is incorporated by reference herein in its entirety.

Processes for aligning lens stack arrays with sensors in accordance with many embodiments of the invention involve aligning the lens stack arrays with respect to sensors so as to enhance the resulting array camera module's ability to produce high-resolution images using super-resolution processes. Super-resolution refers to the process of synthesizing a plurality of low-resolution images of a particular scene—each image providing a sub-pixel shifted view of that scene (i.e. the object space sampled by the pixels is shifted relative to the other images captured by the array camera)—to derive a corresponding high-resolution image. Essentially, in a super-resolution process, sampling diversity between the low resolution images of a scene captured by an array camera module is utilized to synthesize one or more high resolution images of the scene. Thus, an array camera can capture and record a plurality of low-resolution images, and employ a super-resolution algorithm to generate a high-resolution image. Super-resolution processes that can be used to synthesize high resolution images from a plurality of low resolution images of a scene are described in U.S. Patent Publication 2012/014205 entitled "System and Methods for Synthesizing High Resolution Images Using Super-Resolution Processes" published Jun. 14, 2012, the disclosure of which is incorporated by reference herein in its entirety.

The extent to which super-resolution processing can be utilized to obtain an increase in resolution of an image synthesized from a plurality of low resolution images can depend on the sampling diversity and sharpness of the images. Importantly, the sampling diversity of the captured low resolution images is partly a function of the spatial relationship between the lens stack array and the sensor. Thus, many embodiments of the invention further align the lens stack array with the array of focal planes to enhance the sampling diversity within the corresponding array camera module by discovering and implementing a spatial relationship between the lens stack array and the sensor that enables this result.

Array cameras and systems and methods for correcting warpage of a sensor of an array camera module by manufacturing lens stack arrays that include warpages that at least partially corrects for the warpage in the sensor in accordance with embodiments of the invention are discussed further below.

#### Array Camera Architectures

A variety of architectures can be utilized to construct an array camera using one or more array camera modules and a processor, including (but not limited to) the array camera architectures disclosed in U.S. Application Publication 2011/0069189. A representative array camera architecture incorporating an array camera module incorporating a warped sensor and a lens stack array incorporating warpage that at least partially corrects for the warpage in the sensor and a processor is illustrated in FIG. 1. The array camera **100** includes an array camera module **110**, which is connected to an image processing pipeline module **120** and to a controller **130**. In the illustrated embodiment, the image processing pipeline and the controller **130** are implemented using a processor. In various embodiments, the image processing pipeline module **120** is hardware, firmware, software, or a combination for processing the images received from the array camera module **110**. The image processing pipeline module **120** is capable of processing multiple images captured by



multiple focal planes in the camera module and can produce a synthesized higher resolution image. In a number of embodiments, the image processing pipeline module **120** provides the synthesized image data via an output **122**.

In many embodiments, the controller **130** is hardware, software, firmware, or a combination thereof for controlling various operational parameters of the array camera module **110**. The controller **130** receives inputs **132** from a user or other external components and sends operation signals to control the array camera module **110**. The controller can also send information to the image processing pipeline module **120** to assist processing of the images captured by the focal planes in the array camera module **110**.

Although specific array camera architecture is illustrated in FIG. **1**, camera modules incorporating a warped sensor and a lens stack array incorporating warpage that at least partially corrects for the warpage in the sensor in accordance with embodiments of the invention can be utilized in any of a variety of array camera architectures. Camera modules that can be utilized in array cameras and processes for manufacturing array camera modules in accordance with embodiments of the invention are discussed further below.

#### Array Camera Modules

An array camera module may be formed by aligning a lens stack array and an imager array. Each lens stack in the lens stack array can include an aperture that defines a separate optical channel. The lens stack array may be mounted to an imager array that includes a focal plane for each of the optical channels, where each focal plane includes an array of pixels or sensor elements configured to capture an image. When the lens stack array and the imager array are combined with sufficient precision, the array camera module can be utilized to capture image data from multiple views of a scene that can be read out to a processor for further processing, e.g., to synthesize a high resolution image using super-resolution processing.

An exploded view of an array camera module formed by combining a lens stack array with a monolithic sensor including an array of focal planes in accordance with an embodiment of the invention is illustrated in FIG. **2**. The array camera module **200** includes a lens stack array **210** and a sensor **230** that includes an array of focal planes **240**. The lens stack array **210** includes an array of lens stacks **220**. Each lens stack creates an optical channel that resolves an image on the focal planes **240** on the sensor. Each of the lens stacks may be of a different type. For example, the optical channels may be used to capture images at different portions of the spectrum and the lens stack in each optical channel may be specifically optimized for the portion of the spectrum imaged by the focal plane associated with the optical channel. More specifically, an array camera module may be patterned with “ $\pi$  filter groups.” The term  $\pi$  filter groups refers to a pattern of color filters applied to the lens stack array of a camera module and processes for patterning array cameras with  $\pi$  filter groups are described in U.S. Patent Publication 2013/0293228, entitled “Camera Modules Patterned with  $\pi$  Filter Groups”, Venkataraman et al. The disclosure relevant to  $\pi$  filter groups in U.S. Patent Publication 2013/0293228 is incorporated by reference herein in its entirety. FIG. **3** illustrates a single  $\pi$  filter group, wherein 5 lenses are configured to receive green light, 2 lenses are configured to receive red light, and 2 lenses are configured to receive blue light. The lens stacks may further have one or multiple separate optical elements axially arranged with respect to each other.

A lens stack array may employ wafer level optics (WLO) technology. WLO is a technology that encompasses a number of processes, including, for example, molding of lens arrays

on glass wafers, stacking of those wafers (including wafers having lenses replicated on either side of the substrate) with appropriate spacers, followed by packaging of the optics directly with the imager into a monolithic integrated module.

The WLO procedure may involve, among other procedures, using a diamond-turned mold to create each plastic lens element on a glass substrate. More specifically, the process chain in WLO generally includes producing a diamond turned lens master (both on an individual and array level), then producing a negative mould for replication of that master (also called a stamp or tool), and then finally forming a polymer replica on a glass substrate, which has been structured with appropriate supporting optical elements, such as, for example, apertures (transparent openings in light blocking material layers), and filters.

Although the construction of lens stack arrays using specific WLO processes is discussed above, any of a variety of techniques can be used to construct lens stack arrays, for instance those involving precision glass molding, polymer injection molding or wafer level polymer monolithic lens processes. Issues related to variation in back focal length of the lens stacks within lens stack arrays are discussed below.

#### Back Focal Plane Alignment

An array camera module is typically intended to be constructed in such a way that each focal plane (i.e. an array of pixels configured to capture an image formed on the focal plane by a corresponding lens stack) is positioned at the focal distance of each lens stack that forms an optical channel. However, manufacturing variations can result in the lens stack in each optical channel varying from its prescription, and in many instances, these variations can result in each lens stack within a lens stack array having a different focal length. For example, parameters that may vary amongst individual lens stacks in a lens stack array because of manufacturing variations include, but are not limited to: the radius of curvature in individual lenses, the conic, higher order aspheric coefficient, refractive index, thickness of the base layer, and/or overall lens height. As one of ordinary skill in the art would appreciate, any number of lens prescriptions may be used to characterize the lens fabrication process, and the respective tolerances may involve departures from these prescriptions in any number of ways, each of which may impact the back focal length. Due to the monolithic nature of the sensor, the spatial relationship of the focal planes (with respect to the lens stacks) cannot be individually customized to accommodate this variability.

The variations in focal length that can occur in a conventional lens stack array are conceptually illustrated in FIG. **4**. The array camera module **400** includes a lens stack array **402** in which lens stacks **404** focus light on the focal planes **406** of sensor **408**. As is illustrated, variance between the actually fabricated lens stack and its original prescription can result in the lens stack having a focal length that varies slightly from its prescription and consequently an image distance that does not correspond with the distance between the lens stack array and the sensor. Accordingly, the images formed on the focal planes of the sensor can be out of focus. In addition, other manufacturing tolerances associated with the assembly of the array camera module including (but not limited to) variations in spacer thickness and alignment of the lens stack array relative to the sensor can impact all of the optical channels. Therefore, as discussed in U.S. Patent Publication 2014/0002674, active alignment processes may be incorporated in the manufacture of array camera modules to mitigate this effect.

One cause of variations in the focal lengths in a lens stack array is warpage of the lens stack array and/or sensor. A side



view of a sensor showing a convex warpage of a sensor in accordance with an embodiment of the invention is shown in FIG. 5. Although warpage is discussed with reference to the sensor, the discussion equally applies to a lens stack array. In FIG. 5, sensor 500 has warpage causing the sensor 500 to have a convex bow. Typically stress induced during the packaging of a sensor, e.g. mounting onto a PCB, leads to a convex bow in a sensor such as sensor 500. By convex, it is understood that convex describes the surface 505 of the sensor 500 that includes the pixel surface bowing outwards from sensor 500 (i.e. in a direction toward the lens stack array to which the sensor will be aligned) with respect to the expected plane 510 of the surface. The warpage may be caused by factors including (but not limited to) CTE mismatches between the material of the sensor and PCB material. For example a sensor generally includes a large amount of silicon and the PCB is made of a material such as, FR4, that has a much larger CTE than silicon. Thus, elevated curing temperatures during bare die and/or CSP attachment process(es) as well as actual board manufacturing processes may introduce the convex warpage into the sensor 500.

A sensor having a concave bow in accordance with embodiments of this invention is shown in FIG. 6. One skilled in the art will recognize that a lens stack array may also have a concave bow and the following discussion also applies to a lens stack array. Sensor 600 has concave bow. One skilled in the art will recognize that a concave bow in a sensor typically does not occur. By concave, it is understood that concave describes the surface 605 of the sensor 600 that includes a pixel surface 605 bowing inwards towards sensor 500 (i.e. in a direction away from the lens stack to which the sensor is aligned).

The lens stack array may also have warpage. Warpage in the lens stack array and/or other factors may cause warpage in the projection plane of the images from lens stack array. The BFL-pattern of the warpage in the projection plane of the lens stack array may vary between concave and convex. It is understood that concave and convex describe the shape of the warpage of the lens stack array with respect to the expected plane of the surface of the pixels in the sensor array as described above with reference to the sensor. In a conventional array camera module, the warpage of the lens stack array may be caused by the lens stack array being introduced into a hold over the sensor and/or a variation of the focal planes from the focal planes of a flat lens stack array.

In accordance with some embodiments of this invention, the effective variations in the back focal lengths of the individual lens in the lens stack array causing warpage in the projection plane of the lens stack array are reduced by matching the warpage of the sensor and the warpage of the projection plane of lens stack array such that the curvature signs of the bows for each warpage are substantially equal to one another. The equality of the shape of the deformation in the sensor and the projection plane of the images formed by the lens stack array results in an effective defocusing pattern in the array camera that is substantially free of the bow. The resulting effective variation in the Back Focal Length (BFL) pattern of the array camera module is decreased. The placement of the lens stack array over the sensor in accordance with embodiments of the invention is shown in FIG. 7. In FIG. 7, lens stack array 710 is positioned over sensor 720 such that each individual lens stack 711 is aligned with an individual focal plane of pixels 721 to form array camera module 700.

The warpage of each of the lens stack array and sensor of an array camera module in accordance with an embodiment of the invention is shown in FIG. 8. In FIG. 8, sensor 720 has a curvature that is convex in that the warpage causes a pixel

surface of sensor 720 to bow outward from sensor 720 toward the lens stack array with respect to the expected plane of the surface of pixels in the sensor 720. Lens stack array 710 has a curvature that is convex in that the warpage of lens stack array 710 causes lens stack array 710 to bow outward from sensor (i.e. away from the sensor) with respect to an expected plane of the surface of pixels in the sensor. Thus, when lens stack array 710 is placed over sensor 720 the warpage of lens stack 710 is the substantially equal to the warpage of sensor 720. Thus, the axial alignment between the individual lens and sensors is maintained. More particularly, the equality in the warpage of each component causes the warpage of the projection plane of the images formed by the lens stack to be substantially equal to the warpage of the sensors. Thus, the projected images from the lens stack array have the same focal distance with respect to the sensor. In accordance with other embodiments, the warpage of the projection plane of images other manners including, but not limited to, adjusting the optics in one or more lens stacks in the lens stack array. One skilled in the art will recognize that either component or both components may have different curvatures signs of the bows, the only requirement being that the warpage of the lens stack array corrects for the warpage of the sensor 720 in accordance with some embodiments of this invention.

Processes for manufacturing an array camera module that includes a lens stack array incorporating warpage that at least partially corrects warpage in a sensor in accordance with an embodiment of the invention is illustrate in FIG. 9. Process 900 is a process for manufacturing a single array camera module that includes a lens stack array that has warpage that at least partially corrects warpage in a sensor in accordance with an embodiment of the invention. In process 900, a sensor is manufactured using conventional processes (905). In accordance with some embodiments, the flatness requirements of the sensor are relaxed during the manufacture process of the sensor which includes the mounting of the sensor to a PCB. The warpage of the sensor is then measured (910). In accordance with some embodiments, the measurements include a curvature sign of a bow. In accordance with some embodiments, the measurements are performed using testing equipment and the results are provided to processing system, such as a computer. In some embodiments, the results of the measurement are stored to a memory for later use.

The measurements of the warpage are then used to determine the warpage needed in the projection plane of the images formed by the lens stack array. The required warpage needed is then used to generate a design specification for a lens stack array that provides the desired warpage in the projection plane of the images formed by the lens stack array (915). The design specification is a specification that results in a lens stack array that provides a projection plane that has a warpage that corrects for the warpage in the sensor. In accordance with some embodiments, the correction causes the projection plane of the lens stack array to have of curvature sign of a bow that is the same as that the curvature signs of the sensor. The design specification can be generated by a computer system that receives the measurements from the testing equipment and applies design algorithms to the measurement results to determine the proper design specification based upon the desired warpage of the projection plane.

The design specification is then used to generate a lens stack array to match the measured sensor (920). Conventional processes such as, but not limited to WLO techniques can be used to manufacture the lens stack array in accordance with embodiments of the invention. The manufactured lens stack



## 11

can then be placed over (925) and aligned (930) with the sensor using conventional processes to form an array camera module.

Although specific embodiments of a process for manufacturing an array camera module in accordance with an embodiment of this invention are described above with reference to FIG. 9, other processes may be used to manufacture an array camera module in accordance with other embodiments of this invention.

The making of a specific lens stack array for a specific sensor may be too expensive and too time intensive for mass production of array camera modules. Thus, alternative process for manufacturing array camera modules may use lens stack modules that are configured to correct average warpage of manufactured sensors and/or warpages that are replicated across multiple sensors by the sensor manufacturing process. A flow chart of a process for the mass manufacture of array camera modules having lens stack arrays that are designed to correct the average warpage of manufactured sensors in accordance with an embodiment of this invention is shown in FIG. 10. Process 1000 includes manufacturing a test group of sensors (1005). In accordance with some embodiments, the flatness requirements of the sensors are relaxed during the manufacturing and/or packaging process of the sensors. The warpage of each sensor in the test group of sensors can then be measured (1010). In accordance with some embodiments, the measurements include a determination of the curvature of each sensor. In accordance with many embodiments, the measurements are performed using testing equipment and the results are provided to a processing system, such as a computer. In several embodiments, the results of the measurement are stored to a memory for later use.

The measurements of the warpage of the test group of sensors are then used to determine one or more design specifications for a lens stack array(s) (1015). The design specification is a specification that results in a lens stack array that provides a projection plane of the images formed by the lens having a warpage of the projection plane of the images formed by the lens stack array (either by respective mechanical deformation of the lens stack array itself, or by incorporation of the respective BFL-variation) that at least partially corrects for the average warpage in the test group of sensors. In accordance with some embodiments, the warpage of the projection plane of the lens stack array is achieved by mechanical deformation of the lens stack array itself. In accordance with some other embodiments, the warpage of the projection plane of the lens stack is achieved by BFL-variation of the optics in the individual lens stacks in the array. In accordance with some embodiments, the correction causes the projection plane of the lens stack array to have of a curvature that is identical to the curvature observed in the initial group of sensors. The design specification can be generated by a computer system that receives the measurements from the testing equipment and applies design algorithms to the measurement results to determine the proper design specification for the lens stack array that corrects for the warpage in the sensor.

Sensors can be manufactured in accordance with the previous processes used to manufacture the test group of sensors (1020). The design specification can then be used to generate lens stack arrays to match the manufactured sensors (1025). Conventional processes such as, but not limited to WLO techniques can be used to manufacture the lens stack array in accordance with embodiments of the invention. The manufactured lens stack can then be placed over (1030) and aligned with the sensor (1035) using conventional processes.

## 12

Although specific embodiments of a process for manufacturing array camera modules in accordance with an embodiment of this invention are described above with reference to FIG. 10, other processes may be used to manufacture an array camera module in accordance with other embodiments of this invention.

Although the present invention has been described in certain specific aspects, many additional modifications and variations would be apparent to those skilled in the art. It is therefore to be understood that the present invention may be practiced otherwise than specifically described. Thus, embodiments of the present invention should be considered in all respects as illustrative and not restrictive.

What is claimed is:

1. An array camera comprising:  
an array camera module including:  
a sensor including an array of pixels that is subdivided into a plurality of sub-arrays of pixels, where each of the plurality of sub-arrays forms a focal plane; and  
a lens stack array comprising a plurality of lens stacks wherein each of the plurality of lens stacks includes an aperture and forms an image on a focal plane formed by one of the plurality of sub-array of pixels on the sensor; wherein the surface of the sensor on which images are formed by the lens stack array includes a warpage;  
wherein a projection plane of images formed by the lens stack array incorporates a warpage that at least partially corrects the warpage in the sensor.
2. The array camera of claim 1 wherein the warpage of the sensor has a curvature of a bow that is convex.
3. The array camera of 2 wherein the warpage of the focal plane of the lens stack array has a curvature of a bow that is convex.
4. The array camera of 1 wherein the curvature of the warpage of the focal of the lens stack array is substantially equal to the curvature of the warpage of the sensor.
5. The array camera of claim 1 wherein the warpage of the lens stack array corrects the warpage of the sensor to provide back focal lengths for each of the plurality lens stacks in the lens stack array that are substantially consistent.
6. A method for manufacturing an array camera module comprising:  
manufacturing a sensor including an array of pixels that is subdivided into a plurality of sub-arrays of pixels wherein each of the plurality of sub-arrays forms a focal plane;  
measuring a warpage of the sensor to generate warpage information;  
generating a design for a lens stack array comprising a plurality of lens stacks wherein each of the plurality of lens stacks is associated with a focal plane formed by one of the plurality of sub-array of pixels in the sensor and wherein the lens stack array is configured to have a projection plane of images formed by the lens stack array that has a warpage that corrects the warpage in the sensor based upon the warpage information for the sensor;  
manufacturing the lens stack array in accordance with the generated design; and  
placing the lens stack array over the sensor to form an array camera module.
7. The method of claim 6 further comprising:  
aligning the lens stacks in the lens stack array with focal planes formed by the plurality of sub-arrays in the sensor.
8. The method of claim 6 wherein the warpage of the lens stack array corrects the warpage of the sensor to provide back



**13**

focal lengths for each of the plurality of lens stacks in the lens stack array that are substantially consistent.

**9.** The method of claim **6** wherein the warpage of the sensor has a curvature of a bow that convex.

**10.** The method of **9** wherein the warpage of the projection plane of lens stack array has a curvature of a bow that is convex.

**11.** The method of **9** wherein the curvature of the warpage of the projection plane of the lens stack array is substantially equal to the curvature of the warpage of the sensor.

**12.** The method of claim **6** wherein the flatness requirements for the sensor are relaxed during the manufacturing and packaging of the sensor.

**13.** A method for mass manufacturing an array camera module comprising:

manufacturing a first plurality of sensors wherein each of the plurality of sensors includes an array of pixels that is subdivided into a plurality of sub-arrays of pixels wherein each of the plurality of sub-arrays forms a focal plane;

measuring a warpage of each of the first plurality of sensors to generate warpage information;

generating a design for a lens stack array comprising a plurality of lens stacks wherein each of the plurality of lens stacks is associated with a focal plane formed by one of the plurality of sub-array of pixels in the sensor and wherein the lens stack array is configured to have a projection plane of images formed by the lens stack

**14**

array that has a warpage that corrects the warpage in the sensor based upon the warpage information for the first plurality of sensor;

manufacturing a second plurality of sensors in accordance with a process used to manufacture the first plurality of sensors;

manufacturing a plurality of lens stack arrays in accordance with the generated design; and

placing a one of the lens stack arrays over one of the second plurality of sensors to form array camera modules.

**14.** The method of claim **13** further comprising: aligning the lens stacks in each of the plurality of lens stack arrays with focal planes formed by the plurality of sub-arrays in each of the second plurality of sensors.

**15.** The method of claim **13** wherein the warpage in the lens stack array design corrects the warpage of the first plurality of sensors to provide back focal lengths for each of the plurality of lens stacks in the lens stack array that are substantially consistent when placed over the second plurality of sensors.

**16.** The method of claim **13** wherein the warpage of the first and second plurality of sensors has a curvature of a bow that convex.

**17.** The method of **16** wherein the warpage of the projection planes of the plurality of lens stack arrays have a curvature of a bow that is convex.

**18.** The method of **16** wherein the curvature of the warpage of the projection planes of the plurality of lens stack arrays is substantially equal to a curvature of bow of the warpage of the plurality of sensors.

\* \* \* \* \*